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INTRODUCTION

The Institute for Computer Applications in Science and Engineering (ICASE) is operated at the Langley Research Center (LaRC) of NASA by the Universities Space Research Association (USRA) under a contract with the Center. USRA is a nonprofit consortium of major U. S. colleges and universities.

The Institute conducts unclassified basic research in applied mathematics, numerical analysis, and computer science in order to extend and improve problem-solving capabilities in science and engineering, particularly in aeronautics and space.

ICASE has a small permanent staff. Research is conducted ~~primarily~~ by visiting scientists from universities and from industry, ~~who have resident~~ appointments for limited periods of time, ~~and by~~ consultants. Members of NASA's research staff also may be residents at ICASE for limited periods.

The major categories of the current ICASE research program are:

1) Numerical methods, with particular emphasis on the development and analysis of basic numerical algorithms;

2) Control and parameter identification problems, with emphasis on effective numerical methods;

3) Computational problems in engineering and the physical sciences, particularly fluid dynamics, acoustics, and structural analysis;

4) Computer systems and software for parallel computers.

ICASE reports are considered to be primarily preprints of manuscripts that have been submitted to appropriate research journals or that are to appear in conference proceedings. A list of these reports for the period October 1, 1990 through March 31, 1991 is given in the Reports and Abstracts section which follows a brief description of the research in progress.

[1] Presently, ICASE is operated at NASA Langley Research Center, Hampton, VA, under the National Aeronautics and Space Administration, NASA Contract No. NAS1-18605. In the past, support has been provided by NASA Contract Nos. NAS1-18107, NAS1-17070, NAS1-17130, NAS1-15810, NAS1-16394, NAS1-14101, and NAS1-14472.

RESEARCH IN PROGRESS

Saul Abarbanel

Work continued on three topics reported in the last semiannual report; namely–

- Spurious frequencies due to numerical boundary treatment.
- Accelerating nondiagonalizable hyperbolic systems to steady-state.
- Stability of initial-boundary value problems approximated by high order Pade'-like finite differences.

In addition progress has been made (together with doctoral student Jeffery Danowitz) on constructing long-wave non-reflecting boundary conditions for the viscous flow past finite bodies. At present the flow past a finite flat plate has been coded and preliminary results encourage continuation of this effort.

Part of the work described above is carried out together with David Gottlieb and Mark Carpenter (Fluid Mechanics Division, LaRC).

H. T. Banks and Fumio Kojima

Work is continuing on geometrical heat inverse problems arising in non-destructive evaluation methods. Our concern in this problem is to develop an efficient algorithm for identifying the corrosion profiles inside a body using thermographical data. Together with W. P. Winfree (Instrument Research Division, LaRC), we are developing a practical method for the estimation of the back surface shape using the thermal data from the front surface. Recently, we proposed a spline-based corrosion detection algorithm using the boundary element method. Our aim in this approach is to estimate the geometrical structure of corrosions as well as to detect material flaws. In the algorithm, the material shape is characterized by a periodic B-spline series. Then the problem is formulated as a minimization problem of the output least squares error subject to a Volterra integral equation of the second kind. Preliminary computational experiments were successful using simulation data. We are currently pursuing investigations to prove the existence of solutions for our estimation problem and to analyze convergence properties for the proposed computational method.

H. T. Banks and Ralph Smith

We are continuing the development of a computationally viable infinite-dimensional control and identification methodology for the stable and optimal design of noise suppression systems. The basic approach is to combine approximation theory with time domain state space modeling to develop convergent computational algorithms for LQR control designs.

The physical system being studied consists of chambers which are separated by a flexible plate, and initial efforts have centered around the development of an accurate structure/fluid interaction model which describes the transmission of acoustical pressure waves from one cylindrical cavity to another through the separating flexible plate. This has led to the formulation of a system of partial differential equations consisting of a 3-D wave equation coupled with elasticity equations for the plate. A finite element scheme is being developed to discretize the system and the validity of the model is being tested both numerically and with data from experiments by J. Bayer. H.C. Lester and R.J. Silcox (Acoustics Division, LaRC).

Once the modeling and identification aspects have been completed, the active feedback control of interior pressure will be implemented via structural vibration control. To accomplish this, feedback to piezo ceramic patches in the plate will be used to affect plate moments in a manner which optimally controls the acoustic pressure in the chamber.

Kurt Bryan

Work is underway on a thermo-mechanical inverse problem, namely that of using the mechanical response of a structure to external thermal stimuli to determine its internal properties and/or locate defects. The focus has been on the special case of an isotropic material (thermally and mechanically) with an unknown defect (a hole). Analysis of the forward or direct problem leads to a system of partial differential equations consisting of a heat equation coupled to the linear equations of elasticity. The thermal source is assumed to be periodic in time, so that the elasticity equations also contain inertial terms. Due to the complicated nature of the equations, the computational solution of the inverse problem will likely rely on an optimization/fit-to-data approach requiring an economical scheme for rapidly solving the direct problem. Work so far has centered on deriving such numerical schemes using the method of boundary integral equations. This approach should be particularly efficient since knowledge of the mechanical response of the the object being imaged is required (and can be measured) only on its surface and not in its interior. Coding for a two-dimensional version of the problem is underway.

Work has also continued on the inverse conductivity problem, in which one attempts to identify the internal electrical conductivity of an object from voltage and current flux mea-

surements on its boundary. The special case of identifying a piecewise constant perturbation of a constant reference conductivity has been studied. An efficient numerical algorithm based on the method of boundary integral equations has been implemented for the solution of the direct problem, as well as a linearized version of the direct problem, and it is used in a least squares approach for solving the inverse problem. Performance on numerically generated data has been good and theoretical convergence results have been proven.

John Burns

In earlier work, we have completed a study of several control problems for Burgers' equation. These nonlinear systems were controlled by using linear feedback computed from LQR theory for the linearized models. We established that under standard assumptions the finite element scheme preserved stabilizability and detectability uniformly under approximation. Numerical results also indicated that the LQR controllers smoothed steep gradients. These results provide some insight into the control of nonlinear distributed parameter systems. We are now turning our attention to realistic fluid flow problems and we have the first results on optimal control of the full unsteady Navier-Stokes flow about a cylinder. An ICASE report with Y. R. Ou is in preparation. We plan to continue our efforts on this class of problems.

Richard Carter

The two major methodologies for improving the robustness of nonlinear optimization algorithms are the trust region approach and the linesearch approach. Previous work has established theory predicting extreme robustness of trust region algorithms in the presence of noisy function and gradient evaluations. This robustness has also been confirmed experimentally. However, for the linesearch approach, it is easy to generate pathological examples where the linesearch algorithm will fail for even small amounts of noise in the function and gradient evaluations.

This argues strongly for the selection of the trust region methodology as the method of choice. Although numerical experiments suggest that the worst-case analysis of the linesearch approach is typically overly pessimistic, failures are still encountered at levels of gradient error for which the trust region approach is still robust.

Leon M. Clancy

The ICASE computing environment continued to evolve. Two Sun SPARCstation 2's were purchased along with 6.0Gb of new disk space. All home directories formerly on fluke,

flounder, polaris and croaker were moved to the new servers, which were named icase and cobia. The automount utility was implemented on all ICASE systems which support it in order to keep the home directory pathnames constant even though they were physically moved to different fileservers.

The SPARCstation 2 servers have exceeded expectations as replacements for the old Sun 3 servers, and are each capable of supporting an additional 9.0Gb without stretching the system's limits.

The automount utility implementation mentioned above allowed local disks scavenged from ICASE's earliest SPARCstation 1's to be used as local swap and home directories on carp, grouper, urchin, and dolphin. This provides a performance enhancement for those workstations, yet allows the users's whose home directories reside on the local disks transparent access to all ICASE systems. As disks become available, more workstations will be given this capability.

Thomas W. Crockett

A Sun SPARCstation 1+ was integrated into the iPSC/860 hypercube system as a fileserver, compile server, and remote host. This allows most program development activities to be offloaded from the SRM, resulting in improved reliability and better response for parallel jobs running in the cube. In addition, a direct Ethernet interface to the cube was added, allowing network communications to bypass the SRM, with performance increased by a factor of 5-10. The Ethernet interface also allows files to be transferred directly to and from the Concurrent File System.

The X Window System and Andrew Toolkit were rebuilt and installed under SunOS 4.1.1 on the ICASE Suns.

Thomas W. Crockett and Tobias Orloff

Significant improvements were made to the performance model for our MIMD rendering algorithm. The model now shows good agreement with experimental results across a wide range of scene complexities and varying numbers of processors. Results from the Intel iPSC/860 demonstrate that, while much of the communication overhead can be effectively overlapped with computation, message latency is still the major overhead on large numbers of processors. Hence, distributed memory architectures suitable for parallel rendering should (a) allow computation and communication to overlap, and (b) have minimal message latencies.

Andrew Dando

The behavior of Görtler vortices, and in particular their growth rates, have been investigated for a compressible inviscid flow in a basic two-dimensional boundary layer in the hypersonic limit. This work is to appear as a joint ICASE report with S. Seddougui. The work is being extended to the case of a basic three-dimensional boundary layer flow in an effort to determine what effect crossflow has on the stability of these Görtler vortices.

Peter W. Duck

The linear stability of compressible plane Couette flow is being investigated. The proper basic velocity and temperature distributions are perturbed by a small amplitude, normal mode disturbance. The full small amplitude disturbance equations are being solved numerically at finite Reynolds numbers, and the inviscid limit of these equations is being investigated in some detail. It has been found that instability can occur, although the stability characteristics of the flow are quite different from unbounded flows. The effects of viscosity are also calculated, asymptotically, and have a stabilizing role in all the cases investigated. Exceptional regimes to the problem occur when the wavespeed of the disturbances approaches the velocity of either of the walls, and these regimes are also being analyzed in some detail. Finally, the effect of imposing radiation-type boundary conditions on the upper (moving) wall (in place of impermeability) is being investigated, and this yields results common to both bounded and unbounded flows. The research is being done in collaboration with G. Erlebacher and M. Y. Hussaini.

Thomas Eidson

A project to study the performance of typical CFD codes on the Intel iPSC/860 was begun. The study includes single node performance as well as the modification of typical CFD algorithms for parallel performance (better load balance and communication). In collaboration with Joel Saltz and Kay Crowley, the code transformations determined useful in the above study are being used as design goals to evaluate and possibly develop code transformation tools and compilers.

Initially, the work focused on studying basic hypercube operations– node communication and single node performance (cache management and assembly coding of vector operations). A vector library was developed (partially) and a programming strategy for that library was studied. When the relevant data is in the data cache, the vector library routines can attain 37 Mflops (40 theoretical peak) for simple vector operations and 55 Mflops (80 peak) for chaining operations. In more realistic kernels with typical data flow patterns where sufficient data

does not always stay in cache, rates vary from 7 to 20 Mflops. Node communication will reduce these single node rates further for a typical code. These single node rates using the library are faster than those attained with the PGI compiler but the speed-up is usually less than 2. The PGI compiler does partial vectorization and has a limited vector library. Work is continuing on optimizing the current vector library/programming strategy and studying other approaches.

An explicit, finite-difference code developed by Gordon Erlebacher to study 3-D, compressible turbulence is being converted to the hypercube to evaluated various performance programming ideas. The first kernel being studied is a periodic tridiagonal solver with multiple right-hand sides. Several data structures and algorithm approaches are being coded and studied.

Gordon Erlebacher

Work on shear flow compressible turbulence in collaboration with S. Sarkar and M.Y. Hussaini has been completed. The shear flow code has been debugged and first results analyzed. A report has been written and accepted in the journal of Theoretical and Computational Fluid Dynamics. Eigenvalue/eigenvector analysis combined with statistical methods is used to analyze the shear flow data. The objective is to correlate the visual pictures of streaks with more quantitative diagnostics.

In collaboration with M.Y. Hussaini and M. Malik and C.-L. Chang (High Technology Inc.), the Parabolized Stability formulation applied to supersonic flows over boundary-layers has been completed. Both the linear and the nonlinear PSE has been implemented and checked. The nonlinear 2-D PSE was checked against second mode data generated in 1988. Results of this work will be presented in Hawaii. The programming was performed by C.-L. Chang.

Together with T.A. Zang (Fluid Dynamics Division, LaRC) and D. Pruett (National Research Council Fellow), direct numerical simulations of supersonic transitional flow over boundary-layers were completed. Simulations were performed of flows over sharp cones at zero angle of attack at a free-stream Mach number of 8. Shape factors were computed and qualitative comparisons of Reynolds stress plots with experimental results were done. Good qualitative agreement was obtained. An ICASE report was completed.

Work with P. Duck and M.Y. Hussaini on the stability of compressible plane Couette flow has produced new types of instabilities. This work combines asymptotics of high Reynolds number flows with linear stability calculations of the linearized Navier-Stokes equations as finite Reynolds number to clarify some of the mechanisms that lead to unstable modes in the supersonic regimes. In this work, we tried to relate the modes found in Couette flow

with those known to exist in supersonic boundary layers. An ICASE report describing this work has been completed.

Work is in progress with S. Biringen at Colorado State University on the Direct Numerical Simulation of compressible Couette flow.

James F. Geer

Work is continuing on hybrid perturbation/variational techniques for solving a variety of problems for both ordinary and partial differential equations. For ODE's, we are currently applying the methods to several classes of nonlinear vibration problems, with special emphasis on resonant frequency calculations for systems of equations. For PDE's, we are investigating how the method might be applied to some exterior boundary value problems for elliptic PDE's, when the boundary of the domain D has an irregular shape. The basic idea is to treat D as a perturbation of a simple domain R (e.g. a circle or an ellipse, in two dimensions) by embedding it in a one parameter family of domains indexed by a parameter a, where $0 \leq a \leq 1$. Currently, we are applying the method to some eigenvalue problems for irregularly shaped domains and to some problems of flows about geometrically complicated bodies. In addition, we are combining our method with some homotopy methods to further enhance the accuracy of the results we obtain. In particular, we hope this will lead to a new extension of slender body theory. So far, the preliminary results have been done with C. Andersen (College of William and Mary), while possible applications are being discussed with E. Liu (Fluid Mechanics Division, LaRC) and M. Hemsch (Lockheed Engineering and Science Co.).

Investigations are also continuing concerning some fundamental properties of a class of "almost" singular integral equations of the first find which are useful in representing solutions to certain elliptic exterior boundary value problems. These equations typically have the property that the domain of integration R is a proper subset of the domain of validity D of the equation. Special consideration is being given to the idea of analytically continuing the solution into the domain D. In fact, this has now been done for a large class of one-dimensional integrals, such as those which occur in the representation of solutions involving a body of revolution. Application of the results to several two and three dimensional problems involving slender or thin bodies are being carried out. The symbolic manipulation systems MACSYMA and Mathematica have been used in some of the preliminary investigations.

The problem of describing aerodynamically generated sound from compact sources of vorticity is being studied from a perturbation point of view, with the eddy Mach number appearing as the perturbation parameter. The problem appears to be well suited to an application of a slightly modified version of the method of multiple scales. In particular, the

problem of determining the sound generated by a sphere executing arbitrary (small) oscillations in zero mean flow conditions has been investigated successfully by this technique. Once the perturbation solution is fully understood, the hybrid perturbation Galerkin technique will be applied to it, with the goal of extending the usefulness (and accuracy) of the solution to higher Mach numbers than is possible using the perturbation solution alone. This work is being carried out with J. Hardin (Acoustics Division, LaRC).

David Gottlieb

The issue of asymptotic stability, as opposed to Lax stability, becomes more and more important for long time simulations. The notion of Lax stability permits a stable scheme to have a solution that grows exponentially in time; thus a Lax stable scheme may be useless for the numerical simulations of genuinely time dependent problems. We have found that for high order schemes, in particular fourth and sixth order compact finite difference schemes, the numerical inflow boundary condition often induces time growth which renders long time simulations useless. We have developed a theory for checking asymptotic stability for systems of hyperbolic equations and used it to verify that a new boundary treatment based on the penalty method is stable. This work is done with D. Carpenter (Fluid Mechanics Division, LaRC) and S. Abarbanel.

We have continued our work on spectral methods for shock wave calculations.In this context we found a method that completely removes the Gibbs phenomenon, even at the discontinuity. Numerical simulations of two dimensional interactions of shocks and vortices demonstrate the applicability of spectral methods for those problems.

We are looking at domain decomposition methods as means to parallelize spectral methods. To minimize communications we use explicit methods to advance the interface points and implicit methods for the inner domains. A substantial saving has been observed for some parabolic problems.

Philip Hall

Hypersonic boundary layers can be unstable for a variety of different instability mechanisms. We have been investigating the interaction of inviscid, Gortler and Tollmien Schlichting waves in Sutherland Law fluids. The effect of real gas properties and shocks on the instabilities has been studied, as has the effect of compliant walls on vortex instabilities. A new class of exact Navier Stokes solutions has been derived and we have shown the relevance of the solutions to large amplitude instabilities in boundary layer flows. Other work in three dimensional boundary layer instability theory concerns vortex wave interactions and the

interaction of crossflow, Gortler and Tollmien Schlichting modes. The receptivity problem for nonparallel modes in disc flows has been solved. Work is also being carried out on the secondary instability of strongly nonlinear vortex flows in incompressible and compressible boundary layers. This work has already quantitatively reproduced many of the key features of the breakdown structure of streamwise vortices; present work is concentrated on the hypersonic limit of that problem. Work on the instability of heated boundary layers is also in progress.

Thomas L. Jackson

Work focuses on the time evolution on the interaction of a diffusion flame with a vortex, which directly applicable to the large scale structures found in compressible mixing layers. In particular, the ignition process and the resulting structure are under current investigation. A combination of asymptotics and numerics is used to reduce the complex problem to a model problem, thus isolating key physical effects for analysis. This work is in collaboration with M. Macaraeg (Fluid Mechanics Division, LaRC) and M.Y. Hussaini.

Peter A. Jacobs

Work has continued on the simulation of transient, hypervelocity flows in shock tunnels. We attempted to simulate the starting flow in a Mach 8 axisymmetric nozzle and reported the results in ICASE Report 91-1. This attempt was only partially successful and we are currently trying again with an finite-volume upwinding code (see Jacobs and Scroggs). Despite a number of deficiencies, the simulations proved to be useful in guiding the analysis of experimental measurements. Two sets of previously obtained measurements have since been reexamined. ICASE Report 91-24 documents some of the experimental data for a Mach 4 nozzle and a larger Mach 8 nozzle while ICASE Interim Report 16 documents the data for a scramjet combustor experiment.

Peter A. Jacobs and Jeffrey S. Scroggs

We have developed yet another program for the integration of the Navier-Stokes equations on a two-dimensional structured mesh. Although the code currently considers only a single-block grid, the full version of the code will describe a flow domain as a set of abutting blocks, each consisting of a *tensor-product* mesh of quadrilateral cells. The flow field is recorded as cell-average values at cell centers and explicit time-stepping is used to update conserved quantities. Second-order flux-difference splitting (via an Osher-type Riemann solver and

limiter) is used to calculate inviscid fluxes across cell faces while central differences (via the divergence theorem) are used to calculate the viscous fluxes. The unusual features of this program are that it is written in C and makes extensive use of sophisticated data structures to encapsulate the data. The idea of writing the code this way is to make it easier (than traditional FORTRAN codes) to "parallelize" for the MIMD style of parallel computer. The code is intended to be a test-bed for implementation on parallel computers and work, in collaboration with J. Saltz, will continue in the later half of the year.

Harry F. Jordan

Multiprocessors are currently manifest in two distinct forms: shared memory and distributed memory. The distinguishing feature is the level at which system latency resulting from data movement is handled. We are studying the software support for suppressing the distinctions among data based on its location in a message passing multiprocessor and relating the software techniques for algorithm level global referencing to the hardware techniques used to support a shared address space at the machine instruction set level. The key issue is the management of latency involved in data movement. Latency can be reduced by appropriate placement of data or masked by overlapping useful computation with data movement. Data reduction is done by problem mapping in software for distributed memory multiprocessors and by caches in hardware for shared memory machines. Latency masking is done by scheduling message traffic in advance of the need for its data in distributed memory machines and by various forms of pipelining in the hardware of shared memory multiprocessors. Comparing and contrasting the techniques used for latency management in both domains can yield new insight into the best combination of both levels of support for large scale multiprocessors.

In a separate effort, we are studying speed scalable optical computer architectures. These architectures postulate that the speed of signal propagation between gates is commensurate with logic switching speeds. Since the speed of light is the upper limit on information transfer speed, optical computing forms a natural domain to study the fine grain pipelined architectures which result from this postulate. An essential element of these speed of light architectures is relaxing the assumption of instantaneous signal propagation within a sequential circuit clock cycle. We are both developing algorithms based on the above assumptions and working with prototype hardware to explore this new design domain. The connection between this work and that mentioned above is the acceptance of latency as an inherent feature of very large or very fast systems and the use of creative methods to manage that latency.

David E. Keyes

The divide-and-conquer paradigm of iterative domain decomposition, or substructuring, has become a practical tool in computational fluid dynamics applications because of its flexibility in accommodating adaptive refinement through locally uniform (or quasi-uniform) grids, its ability to exploit multiple discretizations of the operator equations, and the modular pathway it provides towards parallelism. Our recent work at ICASE (summarized in ICASE Reports 91-19 and 91-20 and related references therein) has focused on a class of domain-decomposed preconditioners based on non-overlapping subregions and a coarse grid of subdomain vertices. We have evaluated the algebraic convergence rate and the parallelizability of algorithms based on such preconditioners for nonlinear multicomponent systems arising from fluid transport applications and have demonstrated how various local refinements can be incorporated into the composite discrete operator. The parallel testbeds of primary interest are the medium scale MIMD machines, such as the Intel iPSC/860.

D. Glenn Lasseigne

Our research focuses on the interactions of disturbances in the flow field with both reacting and non-reacting shocks. A combination of asymptotics and numerics is used to reduce complex problems to model problems, thus isolating key physical effects for analysis. Specific problems include: the non-linear interactions of vorticity/detonation waves, the effects of heat release on the response of an oblique detonation subjected to wedge oscillations, and the coupling of upstream disturbances and wedge oscillations on the stability of an oblique detonation. The goal is to develop numerical routines which capture the instability modes predicted by linear theory. Other problems include the effects of streamwise vorticity on the stagnation point flow and the effects of more general disturbances on a flame in the viscous stagnation region.

Dimitri Mavriplis

Work is continuing on the use of unstructured meshes for solving computational fluid dynamics problems in both two and three dimensions.

In two dimensions, a viscous turbulent flow solver has been developed. Work has concentrated on the implementation and modification of a multiple field equation turbulence model into the two-dimensional code (ICASE Report 91-11). Research on implicit methods for two-dimensional viscous turbulent flows has also been pursued. An ILU (incomplete LU factorization) preconditioned GMRES implicit iterative solver has been developed in conjunction with V. Venkatakrishnan (Computer Science Corporation, Moffett Field, CA) for

the two-dimensional Euler and turbulent Navier-Stokes equations on unstructured meshes.

In three dimensions, an inviscid flow solver has been developed incorporating adaptive meshing techniques and an unstructured multigrid algorithm, thus enabling the efficient and accurate computation of three-dimensional flow fields about complex configurations. Future work will be directed at implementing the viscous turbulent prediction capability developed in the two-dimensional framework into three dimensions.

In conjunction with J. Saltz, S. Das, and R. Ponnusamy, the single-grid non-adaptive three-dimensional unstructured Euler solver has been implemented on the Intel iPSC/860 using the PARTI primitives. This work is aimed at demonstrating the applicability of the PARTI primitives to practical implementations, and also to employ experience gained from particular implementations to aid in the design or modification of the primitives. The implementation will be extended in the future to include the multigrid acceleration capability and adaptive meshing strategies.

Piyush Mehrotra

Current programming environments for distributed memory machines force the programmer to decompose large data structures into a collection of pieces, each piece being "owned" by a single process. The interaction between pieces is then explicitly specified using the underlying message passing primitives. Decomposing data structures in this way and explicitly specifying communication not only is complex and error prone but also "hardwires" the distributions and algorithmic choices.

We have been developing a high-level programming environment, called Kali, to alleviate some of these problems. In our approach, the code is specified using a global name space in a distribution independent manner. The user, however, controls performance critical issues such as load balancing by specifying the distribution of data through high-level annotations. We have run experiments to show that by using our approach, it is easy for the user to experiment with alternative data distributions with minimal changes to the source code. This is because the complex details of interprocessor communication is the responsibility of the compiler and the run-time environment rather than the programmer. Our system has provision for both static and dynamic distributions and we are continuing to investigate transformations and optimizations needed to efficiently support both within the framework of our system.

Kirsten Morris

Uniform stabilizability of approximations appears to be critical to justifying the use of finite-dimensional approximations in controller design for infinite-dimensional systems. Several general results exist for systems with bounded input operators. However, in boundary control of partial differential equation systems, the input operator is unbounded. A study of the requirements on the approximation scheme in order for uniform stabilizability to hold is being done.

Accelerometers are gaining increasing popularity as sensors in control of structures. They are low in cost, do not need to be frequently recalibrated and are accurate. They are of particular importance in control of large space structures, since unlike displacement sensors, no frame of reference is needed. Despite their practical importance, the theoretical aspects of accelerometers have not been explored.

"Well-posed" control systems have several desirable characteristics: (1) the map from input to state is well-defined and continuous in some sense and, (2) the map from the state to the output is also well-defined and continuous. In addition, an equivalence exists between internal exponential stability and external stability for stabilizable/detectable well-posed systems. It can be shown that structural control systems with accelerometers, are not in general well-posed in the sense of Salamon. This is not surprising, since the output is not a direct measurement of a state.

However, an input-output relation and an equivalence between time and frequency domain behavior of these systems can be obtained. This result justifies the use of frequency domain methods in the design of controllers for such systems. Furthermore, approximation methods based on distance in a graph metric may be used in controller design. This analysis also provides insight into the nature of the "generalized transfer function" which exists for well-posed systems. Work with H.T. Banks to determine whether an equivalence between internal and external stability exists for these control systems is underway.

Collaboration with J. Juang (Structures and Dynamics Division, LaRC) is directed at design techniques for structural control which do not rely on an accurate damping model. Due to the practical advantages of accelerometers, we are currently focusing our efforts on structures with acceleration feedback. J. Juang and A. Bruner (Lockheed Engineering and Science Co.) have implemented an unconditionally stable controller which improves the closed loop damping. We are currently attempting to generalize this approach to obtain a closed loop system which possesses a small settling time over a wide range of open loop structural damping behavior.

Naomi Naik and John Van Rosendale

Multigrid algorithms can solve an elliptic PDE on an n-point mesh in $O(n)$ sequential operations, making them optimal order sequential algorithms. They are also effective parallel algorithms; V-cycle multigrid can solve elliptic PDEs on an n-point mesh in $O(\log^2 n)$ parallel steps. However, though this parallel complexity is reasonable, it is a factor of $\log n$ worse than optimal. This is a direct consequence of the "idle processor problem": parallel architectures do not have enough useful work to do on coarse grid levels.

The Frederickson-McBryan Parallel Multigrid algorithm addresses the "idle processor problem," and improves the constant in the $O(\log^2 n)$ complexity bound somewhat, but does not change the order of complexity. The only apparent way of changing this is to use concurrent iteration, in which all multigrid levels are relaxed simultaneously.

In recent work we have combined the idea of concurrent iteration with use of Fredrickson-McBryan-style multiple coarse grids, to get a concurrent relaxation algorithm which is relatively easy to analyze. The resulting algorithm has parallel complexity $O(\log^\alpha n)$, for $\alpha \in (1,\ 2)$, where the specific value of α depends on the interpolation and smoothing operators used. This is the best parallel complexity bound for multigrid obtained so far.

In another recent development, we have constructed a "robust" point relaxation multigrid algorithm using different kinds of multiple coarse grids. As is well known, multigrid algorithms based on line or plane relaxation in each of the coordinate directions can be "robust," in the sense that their convergence rate is independent of mesh aspect ratio. However, such algorithms are expensive, and parallelize poorly. Consider, for example a three dimensional Chebyshev grid. In this case, only plane-relaxation multigrid suffices. Such algorithms have limited and awkward parallelism, requiring $O(\log^3 n)$ time per V-cycle, or at least $O(\log^4 n)$ time to convergence.

An alternative way of achieving robustness, which avoids line and plane relaxations, is to use different kinds of multiple coarse grids, formed by semi-coarsening separately in each of the coordinate directions. This is an idea due to Wim Mulder, who studied its use in the context of a grid alignment problem for hyperbolic PDEs. We discovered a simple modification of Mulder's algorithm for the elliptic case, which leads to a fast and effective robust multigrid algorithm. The new algorithm is competitive with line relaxation on sequential architectures, and far more attractive on parallel machines.

One interesting idea here is to combine this algorithm with concurrent iteration. The resulting algorithms map very well to a variety of parallel architectures, including SIMD machines like the Connection Machine. In joint work with Joe Dendy of Los Alamos National Laboratory, we are studying the effectiveness of this approach on a variety of difficult elliptic problems, including anisotropic problems with large coefficient jumps. We are also exploring

the generalization of this and other concurrent iteration multigrid algorithms to nonlinear PDEs. A concurrent iteration FAS-style algorithm has been defined, and will soon be tried on a sequence of nonlinear test problems.

David Nicol

Together with A. Rifkin (College of William and Mary) we have developed and are studying an algorithm for optimally partitioning a two dimensional workload in a rectangle into rectangles such that each rectangle has only one neighboring rectangle in each of the four directions (NEWS) of the compass. This property is important on parallel architectures where the cost of communicating with a non-NEWS neighbor is extremely high.

Algorithms for executing trace-driven cache simulations on SIMD architectures are under study with A. Greenberg and B. Lubachevsky (AT& T, Bell Laboratories). We have developed algorithms suitable for simulating a general class of stack replacement policy algorithms, as well as random replacement.

Work on load balancing is continuing with R. Simha (College of William and Mary) and D. Towsky (University of Massachusetts). We are looking at the application of the theory of majorization to problems in statically load balancing a stochastically evolving workload. Majorization permits us to assert that one mapping is better than another in a variety of ways, including expected execution time, variation in execution time, space-time product, and reliability.

In a separate effort with D. Reed, we are developing simulation models and analytic models of dynamic load-balancing policies that choose a destination processor at random. Such policies are easy to implement, although they ignore state information. Our aim is to assess the quality and costs of these types of policies.

Yuh-Roung Ou

In collaboration with John Burns work is continuing on the development of theoretical methods and numerical algorithms for various optimal boundary control problems arising in fluid flow. The main thrust of our current investigation is on simulation and control of an unsteady flow generated by a circular cylinder undergoing a combined (steady or unsteady) rotatory and rectilinear motion.

By treating the rotation rate as a control variable in this model, the fundamental problems associated with the development of the alternate shedding of vortices and the induced body forces on the cylinder are studied numerically. Although this research will cover a wide range of time-dependent rotation rates, the computational experiments so far have been performed

under the following three kinds of rotation: (1) constant speed of rotation, (2) time-harmonic rotatory oscillation, and (3) time-periodic rotation.

We have tested the model against the experimental work of Coutanceau & Ménard with excellent agreement. The numerical results elucidate the significant influence of time-varying rotation upon the characteristics of wake and the process of vortex shedding. Precise understanding of this mechanism in boundary layer control may provide an effective way for lift enhancement and reduction of vortex-induced oscillation. The goal of this work is to contribute a useful systematic algorithm for many practical control design problems of high-performance aero/hydro-vehicles, and to lay a bridge between control theory and the control of fluid flow systems.

Demetrious T. Papageorgiou

Work has been continuing on the stability of compressible wakes and shear layers. In particular the hypersonic limit of the wake stability problem was analyzed, the main finding being that the dominant characteristics are derivable from a local analysis of the vorticity mode in the vicinity of the generalized inflection point of the basic flow. A novel hypersonic stability equation was also derived and analyzed, valid in the far-wake limit where physically, the vorticity layer is no longer asymptotically thin. Other on-going research includes the stability of shear layers with a wake component (with M.Macaraeg, Fluid Mechanics Division, LaRC) and asymptotic long-wave stability of compressible shear layers (with T. Jackson).

Work has also been completed (with Y. Smyrlis) to characterize transitions to chaos for the Kuramoto-Sivashinsky equation, a dissipative partial differential equation. We managed to accurately compute classical routes to chaos according to the theory of period-doubling bifurcations and have found excellent agreement with the dynamics of one dimensional discrete maps; in particular, we have computed both of Feigenbaum's universal constants. Work is under way on two fronts (i) the inclusion of dispersive effects in the equation, (ii) the prediction of the dynamics at different physical parameter values from those in the period-doubling cascade.

Ugo Piomelli

Initial studies for the application of a new model in large-eddy simulation of compressible flows have been performed. The dynamic eddy viscosity model of Germano, Piomelli, Moin and Cabot [*Phys. Fluids A*, **3**(7), 1991] has been reformulated for compressible flows, and its extension to the energy equation has been derived. This model utilizes the energy content of the smallest resolved scales to determine the model constants (analogous to the Smagorinsky

constant and to the turbulent Prandtl number) dynamically. The model constants are, thus, capable of adjusting to the local state of the flow. This feature has been successfully exploited for the simulation of both turbulent and transitional flows. *A priori* tests and simulations of compressible homogeneous isotropic turbulence are under way.

Peter Protzel

In a joint effort with D. Palumbo (Information Systems Division, LaRC), we successfully completed an initial study of the fault-tolerance of a certain type of Artificial Neural Networks (ANNs) that can be used to solve optimization problems. One application that we investigated is an ANN that controls the reallocation of tasks in a fault-tolerant, distributed multiprocessor system. This reallocation is necessary if one of the processors fails and all tasks have to be distributed among the remaining processors as quickly as possible by observing certain constraints and by approximately balancing the load of the processors. Thus, the task allocation is a constrained optimization problem that can be solved by an ANN. However, the ANN then becomes a critical component of the system and the fault-tolerance of the ANN itself is of major concern. In order to study the fault- tolerance, we simulated the operation of the ANN in the presence of different types of component failures. Our results show a surprising degree of fault-tolerance with only a slight performance degradation even after multiple faults. A discussion of the results can be found in an upcoming NASA Technical Paper and an ICASE Report currently in preparation. The conclusion of these studies is, that there are certain application areas where an ANN implemented as an analog VLSI chip could perform critical functions as a component of a hybrid system. The advantage of such an approach is the high speed, low weight and power consumption, and "built-in" fault-tolerance of the ANN, which is especially attractive for long-term missions, where component failures have to be expected but a repair is not possible.

In order to extend the scope of ANN models and application areas considered so far, a new project in cooperation with D. Palumbo and C. Jorgensen (NASA Ames Research Center) investigates new unsupervised learning methods for nonlinear, adaptive control with potential use in autonomous systems. From a fault-tolerant systems perspective, there are three different issues that can be addressed, a failure of the controller, a failure of the plant, and a sudden change in the environmental conditions or external perturbations. For example, an adaptive ANN controlling a robot arm should be able to recover from internal faults, from a sudden increase in the friction of an arm joint, or from a new obstacle in the environment by updating and adjusting its control function. The main problem is to maintain a degree of plasticity of the ANN, but still to guarantee an overall stable behavior.

Work continues on another project in collaboration with C. Jeffries (Clemson University)

that investigates a new associative memory architecture with high order feedback connections. One application that has been successfully implemented is the error correction of block codes transmitted over a noisy channel in a digital communication system. Simulations have shown that the use of the associative memory reduces the achievable bit error rate by up to two orders of magnitude in comparison to conventional methods. We are currently working on a general stability proof of the systems which would extend earlier results that exist only for special cases of the "neuron" transfer function. Furthermore, we plan to investigate extensions of the architecture and different signal processing applications.

Joel Saltz

The activities described below were done in collaboration with S. Berryman, K. Crowley, R. Das, S. Gupta (Old Dominion University), S. Hiranandani, D. Mavriplis, S. Petiton (ETCA, France), R. Ponnusamy, J. Scroggs, and J. Wu (Yale University).

We have developed a protctype compiler which takes as input a Fortran 77 program enhanced with specifications for distributing data. The compiler outputs a message passing program that runs on a distributed memory computer. The runtime support for this compiler is the PARTI library of primitives designed to efficiently support irregular patterns of distributed array accesses and irregular distributed array partitions. This compiler was tested on several NASA kernels, and the performance of the resulting codes was benchmarked on the iPSC/860. A description of the compiler and the associated computational experiments may be found in ICASE Reports 90-59 and 91-13.

We have developed and distributed two new sets of runtime primitives designed to help users handle sparse and unstructured computations. The new primitives incorporate a number of new insights we have had about sparse and unstructured computations. Our new primitives carry out preprocessing that makes it straightforward to produce parallelized loops that are virtually identical in form to the original sequential loops. The importance of this is that it will be possible to generate the same quality object code on the nodes of the distributed memory machine as could be produced by the sequential program running on a single node.

Our new primitives incorporate hash tables; hash tables are used to allow us to recognize situations in which a single off-processor distributed array reference is used several times. The new primitives only fetch a single copy of each unique off-processor distributed array reference. The new primitives also allow us to make much finer distinctions concerning which new data need to be obtained from other processors. In our system, schedules are generated to specify which distributed array elements are to be moved between processors. In the older versions of the primitives, we had to generate each schedule from scratch; we can now

produce a schedule that allows us to obtain only those off-processor elements that have not been previously encountered by a specified set of other schedules. Some of the methods used to accomplish this are described in ICASE Report 90-33 and a full description of this work will be forthcoming.

The new set of primitives have been used to port a 3-D unstructured mesh Euler solver. This work has spurred many improvements in the optimizations carried out by our primitives; we have seen a reduction in communication time in a problem solved on a 50,000 node grid, from 288 seconds to 82 seconds (compared to a computation time of 151 seconds). In this code, the total cost of all preprocessing was less than 2 seconds.

Since the form of the sequential code and the parallelized code was virtually identical, we did not expect the parallelization process to introduce any new inefficiencies beyond those exacted by the preprocessing and by the calls to the primitives. On a smaller problem, we compared the parallel code running on a single node with the sequential code and found only a 2 percent performance degradation.

We have also made progress in the area of primitives for structured mesh adaptive codes and for block structured codes. In block structured codes (such as CFL3D and GASP), solvers are carried out on a varying number of coupled Cartesian meshes. The meshes may be different sizes, and each mesh needs to be mapped to a subset of a machine's processors.

In structured adaptive mesh problems, the relationship between the meshes that define a problem change dynamically. In many of these codes, each computational phase involves only a subset of the declared distributed arrays. Since we want to achieve reasonable load balance in each computational phase, we need to be able to partition the various distributed arrays in an overlapping manner. The distributed array mappings are determined at runtime and may be dynamic.

The primitives aimed at block structured and at structured adaptive problems incorporate geometrical information. These primitives allow users to dynamically initialize multidimensional distributed array mappings as well as to transfer data between irregularly distributed multidimensional arrays. We are currently working on a version of the primitives that will support dynamic array remapping. Some of this work is described in ICASE Report 90-41.

The PARTI runtime support mechanisms are also playing an influential role in a variety of distributed memory compiler development projects in the United States and abroad. The primitives have been distributed to the compiler groups at Rice University, University of Colorado, Cornell University, University of Washington, and University of Vienna among others.

We are also extending this work to SIMD multiprocessors. We are developing a set of MasPar PARTI primitives for the MP-1 built by MasPar Inc. and intend to use them to port

the 3-D unstructured Euler code discussed earlier. We have also carried out a comprehensive benchmarking project involving a comparison of the effects of irregular communications and of problem mapping on the CM-2 built by Thinking Machines Inc. This study was reported in ICASE Report 91-12.

Joel Saltz and D. Mavriplis

The thin layer Navier-Stokes equations are solved for two-dimensional airfoil problems by preconditioned conjugate gradient-like iterative methods. In past work, V. Venkatakrishnan (Computer Science Corporation, Moffett Field, CA) has found the GMRES with incomplete LU factorization as a preconditioner is an excellent scheme for solving linear equations arising from two-dimensional airfoil flow calculations on structured meshes. We have shown that these methods are equally applicable to unstructured grids.

In collaboration with Venkatakrishnan, we have investigated a variety of issues that arise when mapping such iterative methods to vector parallel machines and have characterized their performance. The inner loop of our solver involves computation of upper and lower sparse triangular systems. These triangular matrix solutions can constitute an appreciable percentage of the operations required in the iterative portion of preconditioned Krylov space algorithms. It is consequently essential to efficiently compute these sparse triangular solves. We have performed the optimizations required to vectorize and parallelize these operations on an eight processor Cray Y/MP.

While we achieved satisfactory results in vectorizing the sparse triangular solves, our vector parallel results were still somewhat disappointing. Another approach is to partition a domain into P subdomains and carry out an ILU factorization over each sub-domain. The convergence properties of such a domain decomposition depends on precisely how the domain is subdivided. When we partition the domain in one of our model problems in a judicious manner, we are able to obtain speedups of approximately 4.4 compared to a single domain, vectorized code. There is an overhead of approximately 20% due to extra operations introduced; most of the rest of the overhead appears to be due to the fact that partitioning a problem into subdomains reduces vector lengths. We have investigated several different methods for partitioning unstructured meshes to obtain good convergence and good load balance, and to maximize vector lengths. We have also attempted to model the Cray Y/MP performance so that we can extend our results to deal with future more highly parallel vector machines. These results will appear in the proceedings of the SIAM Conference on Parallel Processing and as an ICASE report.

Sutanu Sarkar

We are engaged in the direct simulation and Reynolds stress modeling of turbulent flows. The case of compressible homogeneous shear flow has been simulated in collaboration with G. Erlebacher and M. Y. Hussaini. The simulations reveal a number of features associated with compressibility, for example, a reduction in the growth rate of the turbulent kinetic energy, the augmentation of the turbulent dissipation rate, and a quasi-equilibrium structure of the dilatational component of the velocity field. We have shown clearly that the reduced growth of turbulent kinetic energy in the compressible case is associated with the compressible dissipation and the pressure-dilatation. We have also obtained results regarding probability density functions and higher-order moments from the simulations. These results indicate that local fluid compressions are more likely than local expansions, and that the compressible velocity component is more intermittent than the vortical velocity component. Reynolds stress modeling for high-speed flows is continuing in collaboration with C. Speziale and T. Gatski (Fluid Mechanics Division, LaRC). We now have a turbulence closure for the averaged Navier-Stokes equations, the Reynolds stress equations and the turbulent dissipation rate. The new compressibility models and the SSG pressure-strain model have been incorporated into this closure. Application of the Reynolds stress closure to the supersonic shear layer and the boundary layer have produced promising results.

Sharon O. Seddougui

Work is continuing on the spatial inviscid instability problem for Görtler vortices in a compressible fluid. The governing equations in the limit of large Görtler number were solved numerically in conjunction with Andrew Dando (University of Manchester) to find the growth rate of the imposed disturbance. We see the appearance of two distinct modes of instability, one of which is almost continuous for large wavenumber. Asymptotic solutions have been obtained for large Mach number and/or large wavenumber. These are used to explain the near-linking of the modes which occur. A joint report with Andrew Dando is being prepared.

The extension of the work by Cowley and Hall (ICASE Report No. 88-72) on the instability of hypersonic flow past a wedge to include the effects of nonlinearity has been completed jointly with Andrew P. Bassom (University of Exeter). We are in the process of writing a report on the results. We found that the disturbance is supercritical i.e. the nonlinear effects are stabilizing and that a stable nonzero equilibrium amplitude is possible.

The work of MacKerrell (Ph.D. thesis, University of Exeter), which investigates the effect of compliant walls on the hydrodynamic stability of a boundary layer flow, has been continued to investigate the effects of nonlinearity. The linear stability analysis shows that the growth

rate of a disturbance may be reduced by having a flexible boundary. It is found that the nonlinear effects are stabilizing and that there is the possibility of an equilibrium solution if the flow is linearly unstable. These results are being prepared for an ICASE Report.

Charles G. Speziale

A compressible second-order closure model for supersonic turbulent flows has been developed in collaboration with S. Sarkar. The model has been tested in a variety of homogeneous and inhomogeneous supersonic turbulent flows and comparisons with the results from physical and numerical experiments are quite favorable. Further tests, and possible refinements of the model, are planned for future research. Additional tests of a recently developed near-wall two-equation turbulence model (ICASE Report No. 90-46) were conducted in collaboration with S. Thangam and R. Abid (Vigyan Research Associates). The model was shown to perform extremely well in two independent near-wall turbulent flows involving adverse pressure gradients and flow separation. A computational study of the performance of two-equation turbulence models for turbulent flow past a backward-facing step was also conducted in collaboration with S. Thangam. It was found that previously reported inaccuracies in the predictions of the standard $K - \varepsilon$ model were overestimated due to inadequate numerical resolution of the flow field. With proper numerical resolution – and with the use of an anisotropic eddy viscosity – the $K - \varepsilon$ model was shown to yield excellent predictions for the backstep problem.

Independent work has continued with T. Gatski (Fluid Mechanics Division, LaRC) and P. Durbin (CTR, Stanford University) on modeling the tensor dissipation rate of turbulence. The work with P. A. Durbin has cast grave suspicions on the general validity of Kolmogorov's hypothesis of local isotropy. This hypothesis – which has served as a cornerstone for most turbulence models – postulates that, at sufficiently high Reynolds numbers, the small scales of an anisotropic, inhomogeneous turbulence are approximately isotropic. If this hypothesis is not valid, models for the tensor dissipation rate could play a crucial role in the development of improved turbulence models. Consequently, future research is planned in this direction.

Eitan Tadmor

We continue our study of the isentropic gasdynamics equations using 'appropriate' kinetic models, which enable – by averaging compactness arguments – derivation of new results on macroscopic regularity. Also, a regularized Chapman- Enskog expansion for scalar conservation laws is studied in ICASE Report No. 90-68, where a bounded (relaxation) approximation of the linearized collision operator is used for high wave numbers.

We continue the development of a convergence analysis for the approximate solution to nonlinear hyperbolic equations.

We are completing our study of entropy stable difference approximations to nonlinear systems of conservation laws.

Finally, we began to study various edge detectors based on the (truncated) Hilbert transform, in the context of spectral data.

Saleh Tanveer

Progress has been made in several areas of fluid dynamics and crystal growth in the presence of convection.

In the area of water waves and the classical Rayleigh-Taylor flow, we found that the characterization of the flow field in terms of singularities in the unphysical domain was useful from a computational viewpoint. Such an approach had the potential of calculating highly convoluted interface and explaining the interaction of bubbles and spikes for the Rayleigh-Taylor flow in terms of interaction of singularities. This work is described in ICASE Report 91-21.

In the initial value problem for an interface in a Hele-Shaw cell, a problem that is ill posed in the absence of surface tension, we found that a convenient first step in the understanding of the regularizing effect of small nonzero surface tension was to embed the zero surface tension problem into a well posed problem by extending the spatial domain to the unphysical region. Small surface tension effects can then be studied perturbatively. We found this approach to be fruitful in explaining highly convoluted interfacial features that are very sensitive to initial conditions. Our approach may be general with possible application to Euler flows and understanding of effect of small viscosity. An ICASE report describing the Hele-Shaw dynamics is currently being prepared.

For the problem of crystal growth in a cylindrical geometry with a forced horizontal thermal gradient, we have some regions of the fifteen parameter space with different dynamics. This has all been done for small values of heat transfer through the side walls. We have scaling results on the relative size of convection terms near the free interface for different ranges of solutal and thermal Rayleigh numbers. Further work is in progress to uncover all other interesting limits.

Siva Thangam

Computational and experimental investigations of turbulent separated flow past a rearward facing step are underway to examine the efficacy of turbulence models. The first phase

of this collaborative effort involving C. Speziale, M.Y. Hussaini, and S. Kjelgaard (Fluid Mechanics Division, LaRC) has primarily been concerned with the use of Reynolds stress closure models. The full Navier-Stokes equations and the transport equations for the turbulence kinetic energy and dissipation are solved using different wall boundary conditions and two-equation turbulence models with isotropic and anisotropic eddy viscosity representations. The computations are performed using a staggered mesh, finite-volume algorithm. The results indicate that the characteristics of the flow field are sensitive to the type of turbulence model, the representation of the wall conditions, and the inflow conditions. It is demonstrated that if the computations were performed such that the inflow and the boundary conditions essentially replicate those in the experiments very good agreement between the experimental and computational results could be achieved. During this phase, the experimental setup was also redesigned with an improved inlet channel and a substantially longer downstream test section. During the second phase, experiments will be performed for a step to channel height ratio of 1:2 at several inflow conditions. Computations also will be performed simultaneously using two-equation turbulence models with isotropic and anisotropic eddy viscosity representations and the predictions will be compared with those from the experiments. In addition, large-eddy simulation of the turbulent flow past the 1:2 rearward facing step will be performed to evaluate the performance of the Reynolds stress closure models. The issues involving the appropriate representation for the subgrid scale stresses will be addressed.

John Van Rosendale

Work done in collaboration with Andrea Overman (Analysis and Computation Division, LaRC) found that spectral methods require frequent global communication, raising a fundamental barrier to their use on parallel architectures. Global communication is needed in both the spectral derivative computation, and in the implicit solves. One can do the implicit solves in several different ways, but one of the best alternatives is to use finite element preconditioning, as pioneered by Deville and Mund. The preconditioning finite element system can in turn be solved by a multigrid algorithm. A well tuned multigrid algorithm adequately solves the preconditioning finite element system in one V-cycle.

To explore the issue of communication in spectral methods, we implemented a three dimensional implicit spectral code for the variable coefficient Helmholtz equation on the Intel iPSC/860. This equation arises frequently in acoustics and in the Uzawa formulation of the incompressible Navier Stokes equation. Our Fourier-spectral code, based on a V-cycle point-relaxation multigrid algorithm achieves utilization of 50% on the ICASE 32 node iPSC/860, for a $64 \times 64 \times 64$ grid; finer grids yield higher utilizations.

Chebyshev-spectral grids are more problematic, since either plane-relaxation based multigrid, or the new robust point-relaxation algorithm is required. We implemented a semicoarsening plane-relaxation algorithm, using concurrent relaxation between planes to increase parallelism. This approach leads to perfect load balance, and is well suited to machines like the iPSC/860, having a modest number of processors. We achieve typical utilizations of about 65%. However, this multigrid algorithm solves the preconditioning finite element systems more thoroughly than necessary, so the new point-relaxation based multigrid algorithms may be preferable. Exploration of this alternative is currently in progress.

REPORTS AND ABSTRACTS

Bernard, Peter S., and Charles G. Speziale: *Bounded energy states in homogeneous turbulent shear flow – An alternative view.* ICASE Report No. 90-66, October 2, 1990, 35 pages. To be submitted to Physics of Fluids A.

The equilibrium structure of homogeneous turbulent shear flow is investigated from a theoretical standpoint. Existing turbulence models, in apparent agreement with physical and numerical experiments, predict an unboundedexponential time growth of the turbulent kinetic energy and dissipation rate; only the anisotropy tensor and turbulent time scale reach a structural equilibrium. It is shown that if vortex stretching is accounted for in the dissipation rate transport equation, then there can exist equilibrium solutions,with bounded energy states, where the turbulence production is balanced by its dissipation. Illustrative calculations are presented for a $k-\epsilon$ model modified to account for vortex stretching. The calculations indicate an initial exponential time growth of the turbulent kinetic energy and dissipation rate for elapsed times that are as large as those considered in any of the previously conducted physical or numerical experiments on homogeneous shear flow. However,vortex stretching eventually takes over and forces a production-equals-dissipation equilibrium with bounded energy states. The validity of this result is further supported by an independent theoretical argument. It is concluded that the generally accepted structural equilibrium for homogeneous shear flow with unbounded component energies is in need of re-examination.

Nicol, David M., and Scott E. Riffe: *A "conservative" approach to parallelizing the sharks world simulation.* ICASE Report No. 90-67, October 2, 1990, 14 pages. To appear 1990 Winter Simulation Conf. Proceedings.

This paper describes how we parallelized a benchmark problem for parallel simulation, the Sharks World. The solution we describe is conservative, in the sense that no state information in saved, and no "rollbacks" occur. Our approach illustrates both the principal advantage and principal disadvantage of conservative parallel simulation. The advantage is that by exploiting lookahead we find an approach that dramatically improves the serial execution time, and also achieves excellent speedups. The disadvantage is that if the model rules are changed in such a way that the lookahead is destroyed, it is difficult to modify the solution to accommodate the changes.

Schochet, Steven, and Eitan Tadmor: *Regularized Chapman-Enskog expansion for scalar conservation laws.* ICASE Report No. 90-68, October 2, 1990, 19 pages. Submitted to the Archive for Mechanics and Analysis.

Rosenau [Phys. Rev. A, 40 (1989), pp. 7193-6] has recently proposed a regularized version of the Chapman-Enskog expansion of hydrodynamics. This regularized expansion resembles the usual Navier-Stokes viscosity terms at law wavenumbers, but unlike the latter, it has the advantage of being a bounded macroscopic approximation to the linearized collision operator.

In this paper we study the behavior of Rosenau regularization of the Chapman-Enskog expansion (R-C-E) in the context of scalar conservation laws. We show that this R-C-E model retains the essential properties of the usual viscosity approximation, e.g., existence

of travelling waves, monotonicity, upper-Lipschitz continuity, etc., and at the same time, it sharpens the standard viscous shock layers. We prove that the regularized R-C-E approximation converges to the underlying inviscid entropy solution as its mean-free path $\varepsilon \downarrow 0$, and we estimate the convergence rate.

Mehrotra, Piyush, and John Van Rosendale: *Programming distributed memory architectures using Kali.* ICASE Report No. 90-69, October 3, 1990, 23 pages. Proceedings of the Workshop on Languages and Compilers for Parallel Computers, MIT/Pitman Press, Fall 1990.

Programming nonshared memory systems is more difficult than programming shared memory systems, in part because of the relatively low level of current programming environments for such machines. This paper presents a new programming environment, Kali, which provides a global name space and allows direct access to remote data values. In order to retain efficiency, Kali provides a system of annotations, allowing the user to control those aspects of the program critical to performance, such as data distribution and load balancing. This paper describes the primitives and constructs provided by our language, and also discusses some of the issues raised in translating a Kali program for execution on distributed memory systems.

Koelbel, Charles, and Piyush Mehrotra: *Compiling global name-space programs for distributed execution.* ICASE Report No. 90-70, October 4, 1990, 36 pages. Submitted to IEEE Transactions on Parallel and Distributed Computing, Special Issue June 1991.

Distributed memory machines do not provide hardware support for a global address space. Thus programmers are forced to partition the data across the memories of the architecture and use explicit message passing to communicate data between processors. In this paper we focus on the compiler support required to allow programmers to express their algorithms using a global name-space. We present a general method for analysis of a high level source program and its translation to a set of independently executing tasks communicating via messages. If the compiler has enough information, this translation can be carried out at compile-time. Otherwise run-time code is generated to implement the required data movement. We describe the analysis required in both situations and present the performance of the generated code on the Intel iPSC/2.

Hall, Philip, and Nicola J. Horseman: *The inviscid secondary instability of fully nonlinear longitudinal vortex structures in growing boundary layers.* ICASE Report No. 90-71, October 10, 1990, 41 pages. Submitted to Journal of Fluid Mechanics.

The inviscid instabilty of a longitudinal vortex structure within a steady boundary layer is investigated. The instability has wavelength comparable with the boundary layer thickness so that a quasi-parallel approach to the instability problem can be justified. The generalization of the Rayleigh equation to such a flow is obtained and solved for the case when the vortex structure is induced by curvature. Two distinct modes of instability are found; these modes correspond with experimental observations on the breakdown process for Görtler vortices.

Bassom, Andrew P., and Philip Hall: *Vortex instabilities in 3D boundary layers: The relationship between Görtler and crossflow vortices.* ICASE Report No. 90-72, October 11, 1990, 76 pages. Submitted to Journal of Fluid Mechanics.

The inviscid and viscous stability problems are addressed for a boundary layer which can support both Görtler and Crossflow vortices. The change in structure of Görtler vortices is found when the parameter representing the degree of three-dimensionality of the basic boundary layer flow under consideration is increased. It is shown that Crossflow vortices emerge naturally as this parameter is increased and ultimately become the only possible vortex instability of the flow. It is shown conclusively that at sufficiently large values of the crossflow there are no unstable Görtler vortices present in a boundary layer which, in the zero crossflow case, is centrifugally unstable. The results suggest that in many practical applications Görtler vortices cannot be a cause of transition because they are destroyed by the 3-D nature of the basic state. In swept wing flows the Görtler mechanism is probably not present for typical angles of sweep of about 20 degrees. Some discussion of the receptivity problem for vortex instabilities in weakly 3-D boundary layers is given; it is shown that inviscid modes have a coupling coefficient marginally smaller than those of the fastest growing viscous modes discussed recently by Denier, Hall and Seddougui (1990). However the fact that the growth rates of the inviscid modes are the largest in most situations means that they are probably the most likely source of transition.

Abarbanel, Saul, and David Gottlieb: *Spurious frequencies as a result of numerical boundary treatments.* ICASE Report No. 90-73, October 12, 1990, 28 pages. To appear in the Proceedings of the Third International Conference on Hyperbolic Systems (invited paper).

The stability theory for finite difference Initial Boundary-Value approximations to systems of hyperbolic partial differential equations states that the exclusion of eigenvalues and generalized eigenvalues is a sufficient condition for stability. The theory, however, does not discuss the nature of numerical approximations in the presence of such eigenvalues.

In fact, as was shown previously [1], for the problem of vortex shedding by a 2-D cylinder in subsonic flow, stating boundary conditions in terms of the primitive (non-characteristic) variables may lead to such eigenvalues, causing perturbations that decay slowly in space and remain periodic time. Characteristic formulation of the boundary conditions avoided this problem.

In this paper, we report on a more systematic study of the behavior of the (linearized) one-dimensional gas dynamic equations under various sets of oscillation-inducing "legal" boundary conditions.

Gottlieb, D., and C. L. Streett: *Quadrature imposition of compatability conditions in Chebyshev methods.* ICASE Report No. 90-74, October 12, 1990, 18 pages. Submitted to Journal of Scientific Computing.

Often, in solving an elliptic equation with Neumann boundary conditions, a compatibility condition has to be imposed for well-posedness. Thiscondition involves integrals of the forcing function.

When pseudospectral Chebyshev methods are used to discretize the partial differential equation, these integrals have to be approximated by an appropriate quadrature formula. The Gauss-Chebyshev (or any variant of it, like the Gauss-Lobatto) formula can not be used here since the integrals under consideration do not include the weight function. A natural

candidate to be used in approximating the integrals is the Clenshaw-Curtis formula, however we show in this paper that this is the wrong choice and it may lead to divergence if time dependent methods are used to march the solution to s.eady state.

We develop, in this paper, the correct quadrature formula for these problems. This formula takes into account the degree of the polynomials involved. We show that this formula leads to a well conditioned Chebyshev approximation to the differential equations and that the compatibilitycondition is automatically satisfied.

Roe, P. L.: *"Optimum" upwind advection on a triangular mesh.* ICASE Report No. 90-75, October 15, 22 pages. To be submitted to Journal of Computational Physics.

For advection schemes based on fluctuation splitting, a design criterion of optimising the time step leads to linear schemes that coincide with those designed for least truncation error. A further stage of optimising the time step using a non-linear positivity criterion, leads to considerable further gains in resolution.

Erlebacher, G., M. Y. Hussaini, C. G. Speziale, and T. A. Zang: *Toward the large-eddy simulation of compressible turbulent flows.* ICASE Report No. 90-76, October 16, 1990, 45 pages. Submitted to the Journal of Fluid Mechanics.

New subgrid-scale models for the large-eddy simulation of compressible turbulent flows are developed and tested based on the Favre-filtered equations of motion for an ideal gas. A compressible generalization of the linear combination of the Smagorinsky model and scale-similarity model, in terms of Favre-filtered fields, is obtained for the subgrid-scale stress tensor. An analogous thermal linear combination model is also developed for the subgrid-scale heat flux vector. The two dimensionless constants associated with these subgrid-scale models are obtained by correlating with the results of direct numerical simulations of compressible isotropic turbulence performed on a 96^3 grid using Fourier collocation methods. Extensive comparisons between the direct and modeled subgrid-scale fields are provided in order to validate the models. A large-eddy simulation of the decay of compressible isotropic turbulence – conducted on a coarse 32^3 grid – is shown to yield results that are in excellent agreement with the fine grid direct simulation. Future applications of these compressible subgrid-scale models to the large-eddy simulation of more complex supersonic flows are discussed briefly.

Jacobs, P. A., R. C. Rogers, E. H. Weidner, and R. D. Bittner: *Flow establishment in a generic scramjet combustor.* ICASE Report No. 90-77, October 16, 1990, 40 pages. Submitted to the AIAA Journal.

The establishment of a quasi-steady flow in a generic scramjet combustor is studied for the case of a time varying inflow to the combustor. Such transient flow is characteristic of the reflected-shock tunnel and expansion-tube test facilities. Several numerical simulations of hypervelocity flow through a straight-duct combusto- ʼith either a side-wall-step fuel injector or a centrally-located strut injector are presented. Comparisons are made between impulsively started but otherwise constant flow conditions (typical of the expansion-tube

or tailored operation of the reflected-shock tunnel) and the relaxing flow produced by the "undertailored" operation of the reflected-shock tunnel. Generally the inviscid flow features, such as the shock pattern and pressure distribution, were unaffected by the time varying inlet conditions and approached steady state in approximately the times indicated by experimental correlations. However, viscous features, such as heat transfer and skin friction, were altered by the relaxing inlet flow conditions.

Papageorgiou, Demetrius T., and Yiorgos S. Smyrlis: *The route to chaos for the Kuramoto-Sivashinsky equation.* ICASE Report No. 90-78, October 19, 1990, 55 pages. Submitted to Theoretical and Computational Fluid Dynamics.

We present the results of extensive numerical experiments of the spatially periodic initial value problem for the Kuramoto-Sivashinsky equation. Our concern is with the asymptotic nonlinear dynamics as the dissipation parameter decreases and spatio-temporal chaos sets in. To this end the initial condition is taken to be the same for all numerical experiments (a single sine wave is used) and the large time evolution of the system is followed numerically. Numerous computations were performed to establish the existence of windows, in parameter space, in which the solution has the following characteristics as the viscosity is decreased: A steady fully modal attractor to a steady bimodal attractor to another steady fully modal attractor to a steady trimodal attractor to a periodic (in time) attractor, to another steady fully modal attractor, to another time-periodic attractor, to a steady tetramodal attractor, to another time-periodic attractor having a full sequence of period-doublings (in the parameter space) to chaos. Numerous solutions are presented which provide conclusive evidence of the periodic-doubling cascades which precede chaos for this infinite-dimensional dynamical system. These results permit a computation of the lengths of subwindows which in turn provide an estimate for their successive ratios as the cascade develops. A calculation based on the numerical results is also presented to show that the period doubling sequences found here for the Kuramoto-Sivashinsky equation, are in complete agreement with Feigenbaum's universal constant of 4.669201609... . Some preliminary work shows several other windows following the first chaotic one including periodic, chaotic and a steady octamodal window; however the windows shrink significantly in size to enable concrete quantitative conclusions to be made.

Smith, R. C., K. L. Bowers and J. Lund: *A fully Sinc-Galerkin method for Euler-Bernoulli beam models.* ICASE Report No. 90-79, October 23, 1990, 44 pages. Submitted to Numerical Methods for Partial Differential Equations.

A fully Sinc-Galerkin method in both space and time is presented for fourth-order time-dependent partial differential equations with fixed and cantilever boundary conditions. The sinc discretizations for the second-order temporal problem and the fourth-order spatial problems are presented. Alternate formulations for variable parameter fourth-order problems are given which prove to be especially useful when applying the forward techniques of this paper to parameter recovery problems. The discrete system which corresponds to the time-dependent partial differential equations of interest are then formulated. Computational issues are discussed and a robust and efficient algorithm for solving the resulting matrix system is outlined. Numerical results which highlight the method are given for problems with both analytic and singular solutions as well as fixed and cantilever boundary conditions.

Piomelli, Ugo, and Thomas A. Zang: *Large-eddy simulation of transitional channel flow.* ICASE Report No. 90-80, November 5, 1990, 14 pages. To appear in Computer Physics Communications.

A large-eddy simulation (LES) of transition in plane channel flow has been carried out. The LES results have been compared with those of a fine direct numerical simulation (DNS), and with those of a coarse DNS that uses the same mesh as the LES, but no residual stress model. While at the early stages of transition LES and coarse DNS give the same results, the presence of the residual stress model was found to be necessary to predict accurately mean velocity and Reynolds stress profiles during the late stages of transition (after the second spike stage). The evolution of single Fourier modes is also predicted more accurately by the LES than by the DNS. As small scales are generated, the dissipative character of the residual stress starts to reproduce correctly the energy cascade; as transition progresses, then, and the flow approaches its fully developed turbulent state, the subgrid scales tend towards equilibrium and the model becomes more accurate.

Shaw, Stephen J., and Peter W. Duck: *The inviscid stability of supersonic flow past heated or cooled axisymmetric bodies.* ICASE Report No. 90-81, November 30, 1990, 53 pages. Submitted to Physics of Fluids.

The inviscid, linear, non-axisymmetric, temporal stability of the boundary layer associated with the supersonic flow past axisymmetric bodies (with particular emphasis on long thin, straight circular cylinders), subject to heated or cooled wall conditions is investigated. The eigenvalue problem is computed in some detail for a particular Mach number of 3.8, revealing that the effect of curvature and the choice of wall conditions both have a significant effect on the stability of the flow.

Both the asymptotic, large azimuthal wavenumber solution and the asymptotic, far downstream solution are obtained for the stability analysis and compared with numerical results. Additionally, asymptotic analyses valid for large radii of curvature with cooled/heated wall conditions, are presented. We find, in general, important differences exist between the wall temperature conditions imposed in this paper and the adiabatic wall conditions considered previously.

Jackson, T. L., and C. E. Grosch: *Zero wavenumber modes of a compressible supersonic mixing layer.* ICASE Report No. 90-82, December 3, 1990, 12 pages. To be submitted to Physics of Fluids A.

In this paper we show that there exists a family of supersonic neutral modes for a compressible mixing layer in an unbounded domain. These modes have zero wavenumber and frequency with non-zero phase speed. They are analogous to the supersonic neutral modes of the compressible vortex sheet found by Miles. The results presented here give a more complete picture of the spectrum of the disturbances in this flow.

Liandrat, J., and Ph. Tchamitchian: *Resolution of the 1D regularized Burgers equation using a spatial wavelet approximation.* ICASE Report No. 90-83, December 5, 1990, 36 pages. Submitted to Annales Institut Henri Poincaré.

The Burgers equation with a small viscosity term, initial and periodic boundary conditions is resolved numerically using a spatial approximation constructed from an orthonormal basis of wavelets.

The algorithm is directly derived from the notions of multiresolution analysis and tree algorithms. Before the numerical algorithm is described these notions are first recalled. The method uses extensively the localization properties of the wavelets in the physical and Fourier spaces. Moreover, we take advantage of the fact that the involved linear operators have constant coefficients. Finally, the algorithm can be considered as a time marching version of the tree algorithm.

The most important point is that an adaptative version of the algorithm exists: it allows one to reduce in a significant way the number of degrees of freedom required for a good computation of the solution.

Numerical results and description of the different elements of the algorithm are provided in combination with different mathematical comments on the method and some comparison with more classical numerical algorithms.

Denier, J. P., and Philip Hall: *The effect of wall compliance on the Görtler vortex instability.* ICASE Report No. 90-84, December 6, 1990, 15 pages. Submitted to Physics of Fluids.

The stability of the flow of a viscous incompressible fluid over a curved compliant wall to longitudinal Görtler vortices is investigated. The compliant wall is modeled by a particularly simple equation relating the induced wall displacement to the pressure in the overlying fluid. Attention is restricted to the large Görtler number regime; this regime being appropriate to the most unstable Görtler mode. The effect of wall compliance on this most unstable mode is investigated.

Fu, Yibin B., Philip Hall, and Nicholas D. Blackaby: *On the Görtler instability in hypersonic flows: Sutherland law fluids and real gas effects.* ICASE Report No. 90-85, December 11, 1990, 70 pages. Submitted to Proc. Roy. Soc.

The Görtler vortex instability mechanism in a hypersonic boundary layer on a curved wall is investigated in this paper. Our aim is to clarify the precise roles of the effects of boundary layer growth, wall cooling and gas dissociation in the determination of stability properties. We first assume that the fluid is an ideal gas with viscosity given by Sutherland's law. It is shown that when the free stream Mach number M is large, the boundary layer divides into two sublayers: a wall layer of $O(M^{3/2})$ thickness over which the basic state temperature is $O(M^2)$ and a temperature adjustment layer of $O(1)$ thickness over which the basic temperature decreases monotonically to its free stream value. Görtler vortices which have wavelength comparable with the boundary layer thickness (i.e., have local wavenumber of order $M^{-3/2}$) are referred to as wall modes. We show that their downstream evolution is governed by a set of parabolic partial differential equations and that they have the usual features of Görtler vortices in incompressible boundary layers. As the local wavenumber increases, the neutral

Görtler number decreases and the centre ofvortex activity moves towards the temperature adjustment layer. Görtler vortices with wavenumber of order one or larger must necessarily be trapped in the temperature adjustment layer and it is this mode which is the most dangerous. For this mode, we find that the leading order term in the Görtler number expansion is independent of the wavenumber and is due to the curvature of the basic state. This term is also the asymptotic limit of the neutral Görtler numbers of the wall mode. To determine the higher ordercorrection terms in the Görtler number expansion, we have to distinguish between two wall curvature cases. When the wall curvature is proportional to $(2x)^{-3/2}$ where x is the streamwise variable, the Mach number M can be scaled out of the problem and we show that in the $O(1)$ wavenumber regime, Görtler vortices are again governed by a set of parabolicpartial differential equations and therefore the higher order correction terms in the Görtler number expansion are not uniquely determined and are strongly dependent on nonparallel effects. In the large wavenumber limit, however, nonparallel effects become of second order; Görtler vortices evolve downstream in a quasiparallel manner and the Görtler number expansion has its first three terms independent of nonparallel effects. In the more general case when the wall curvature is not proportional to $(2x)^{-3/2}$, the effect of the curvature of the basic state persists in the downstream development of Görtler vortices; non-parallel effects are important over a larger range of wavenumbers and they become a second order only when the wavenumber is of order higher than $O(M^{1/4})$. In the latter case the Görtler number expansion has the first two terms independent of nonparallel effects; the first term being due to the curvature of the basic state and the second term due to viscous effects. The second term becomes comparable with the first term when the wavenumber reaches the order $M^{3/8}$, in which case another correction term can also be found independently of nonparallel effects. Next we investigate real gas effects by assuming that the fluid is an ideal dissociating gas. We find that both gas dissociation and wall cooling are destabilizing for the mode trapped in the temperature adjustment layer, but for the wall mode trapped near the wall the effect of gas dissociation can be either destabilizing or stabilizing.

Hall, Philip, and P. Balakumar: *On a class of unsteady three-dimensional Navier Stokes solutions relevant to rotating disc flows: Threshold amplitudes and finite time singularities.* ICASE Report No. 90-86 December 10, 1990, 45 pages. Submitted to JFM.

A class of exact steady and unsteady solutions of the Navier Stokes equations in cylindrical polar coordinates is given. The flows correspond to the motion induced by an infinite disc rotating with constant angular velocity about the z-axis in a fluid occupying a semi-infinite region which, at large distances from the disc, has velocity field proportional to $(x, -y, 0)$ with respect to a Cartesian coordinate system. It is shown that when the rate of rotation is large Karman's exact solution for a disc rotating in an otherwise motionless fluid is recovered. In the limit of zero rotation rate a particular form of Howarth's exact solution for three-dimensional stagnation point flow is obtained. The unsteady form of the partial differential system describing this class of flow may be generalized to time-periodic equilibrium flows. In addition the unsteady equations are shown to describe a strongly nonlinear instability of Karman's rotating disc flow. It is shown that sufficiently large perturbations lead to a finite time breakdown of that flow whilst smaller disturbances decay to zero. If the stagnation point flow at infinity is sufficiently strong the steady basic states become linearly unstable. In fact there is then a continuous spectrum of unstable eigenvalues of the stability equations but, if the initial value problem is considered, it is found that, at large values of time, the continuous spectrum leads to a velocity field growing exponentially in time with an amplitude decaying algebraically in time.

Garbey, Marc, and Jeffrey S. Scroggs: *Asymptotic-Induced numerical methods for conservation laws.* ICASE Report No. 90-87, December 12, 1990, 24 pages. Proceedings of Asymptotic Analysis and Numerical Solution of Partial Differential Equations.

Asymptotic-induced methods are presented for the numerical solution of hyperbolic conservation laws with or without viscosity. The methods consist of multiple stages. The first stage is to obtain a first approximation by using a first-order method, such as the Godunov scheme. Subsequent stages of the method involve solving internal-layer problems identified by using techniques derived via asymptotics. Finally, a residual correction increases the accuracy of the scheme. The method is derived and justified with singular perturbation techniques.

Speziale, Charles G., Rishi Raj, and Thomas B. Gatski: *Modeling the dissipation rate in rotating turbulent flows.* ICASE Report No. 90-88, December 12, 1990, 28 pages. To appear in Recent Developments in Turbulence, (Springer-Verlag).

A variety of modifications to the modeled dissipation rate transport equation that have been proposed during the past two decades to account for rotational strains are examined. The models are subjected to two crucial test cases: the decay to isotropic turbulence in a rotating frame and homogeneous shear flow in a rotating frame. It is demonstrated that these modifications do not yield substantially improved predictions for these two test cases and in many instances give rise to unphysical behavior. An alternative proposal, based on the use of the tensor dissipation rate, is made for the development of improved models.

Balakumar, P., P. Hall, and M. R. Malik: *On the receptivity and non-parallel stability of travelling disturbances in rotating disk flow.* ICASE Report No. 90-89, December 12, 1990, 31 pages. Submitted to Theoretical and Computational Fluid Dynamics.

The generation and evolution of small amplitude long wavelength travelling disturbances in rotating disk flow is the subject of this paper. The steady rotational speed of the disk is perturbed so as to introduce high frequency oscillations in the flow field. Secondly, we introduce surface imperfections on the disk such as roughness elements. The interaction of these two disturbances will generate the instabilty waves whose evolution is governed by parabolic partial differential equations which are solved numerically. It is found that, for the class of disturbances considered here (wavelength on the order of Reynolds number), eigensolutions exist which decay or grow algebraically in the radial direction. However, these solutions grow only for frequencies larger than 4.58 times the steady rotational speed of the disk. The computed receptivity coefficient shows that there is an optimum size of roughness for which these modes are excited the most. The width of these roughness elements in the radial direction is about $.1r_0^*$ where r_0^* is the radial location of the roughness. It is also found that the receptivity coefficient is larger for a negative spanwise wavenumber than for a positive one. Typical wave angles found for these disturbances are about -26^o.

Narasimha, R.: *Modelling the transitional boundary layer.* ICASE Report No. 90-90, December 17, 1990, 22 pages. Submitted to Applied Mechanics Review.

Recent developments in the modelling of the transition zone in the boundary layer are reviewed (the zone being defined as extending from the station where intermittency begins to depart from zero to that where it is nearly unity). The value of using a new non-dimensional spot formation rate parameter, and the importance of allowing for so-called subtransitions within the transition zone, are both stressed. Models do reasonably well in constant pressure 2-dimensional flows, but in the presence of strong pressure gradients further improvements are needed. The linear combination approach works surprisingly well in most cases, but would not be so successful in situations where a purely laminar boundary layer would separate but a transitional one would not. Intermittency-weighted eddy viscosity methods do not predict peak surface parameters well without the introduction of an overshooting transition function whose connection with the spot theory of transition is obscure.

Suggestions are made for further work that now appears necessary for developing improved models of the transition zone.

Jacobs, Peter A.: *Transient, hypervelocity flow in an axisymmetric nozzle.* ICASE Report No. 91-1, January 2, 1991, 52 pages. To be submitted as an AIAA paper.

This study examines the performance of an axisymmetric nozzle which was designed to produce uniform, parallel flow with a nominal Mach number of 8. A free-piston-driven shock tube was used to supply the nozzle with high-temperature, high-pressure test gas. Performance was assessed by measuring Pitot pressures across the exit plane of the nozzle and, over the range of operating conditions examined, the nozzle produced satisfactorily test flows. However, there were flow disturbances that persisted for significant times after flow initiation.

The detailed starting process of the nozzle was also investigated by performing numerical simulations at several nominal test conditions. The *classical* description of the starting process, based on a quasi-one-dimensional model, provided a reasonable approximation and was used to demonstrate that the starting process could consume a significant fraction of the otherwise usable test gas. This was especially important at high operating enthalpies where nozzle supply conditions were maintained for shorter times. Multidimensional simulations illustrated a mechanism by which the starting process in the actual nozzle could take longer than that predicted by the quasi-one-dimensional analysis. However, the cause of the persistent disturbances observed in the experimental calibration was not identified.

Ta'asan, Shlomo: *"One shot" methods for optimal control of distributed parameters systems I: Finite dimensional control.* ICASE Report No. 91-2, January 8, 1991, 22 pages. Submitted to SIAM Journal on Optimization.

This paper discusses the efficient numerical treatment of optimal control problems governed by elliptic PDE's and systems of elliptic PDE's, where the control is finite dimensional. Distributed control as well as boundary control cases are discussed. The main characteristic of the new methods is that they are designed to solve the full optimization problem directly, rather than accelerating a descent method by an efficient multigrid solver for the equations involved. The methods use the adjoint state in order to achieve efficient smoother and a

robust coarsening strategy. The main idea is the treatment of the control variables on appropriate scales, i.e., control variables that correspond to smooth functions are solved for on coarse grids depending on the smoothness of these functions. Solution of the control problems is achieved with the cost of solving the constraint equations about two to three times (by a multigrid solver). Numerical examples demonstrate the effectiveness of the method proposed in distributed control case, pointwise control and boundary control problems.

Crockett, Thomas W., and Tobias Orloff: *A parallel rendering algorithm for MIMD architectures.* ICASE Report No. 91-3.

Applications such as animation and scientific visualization demand high performance rendering of complex three dimensional scenes. To deliver the necessary rendering rates, highly parallel hardware architectures are required. The challenge is then to design algorithms and software which effectively use the hardware parallelism. This paper describes a rendering algorithm targeted to distributed memory MIMD architectures. For maximum performance, the algorithm exploits both object-level and pixel-level parallelism. The behavior of the algorithm is examined both analytically and experimentally. Its performance for large numbers of processors is found to be limited primarily by communication overheads. An experimental implementation for the Intel iPSC/860 shows increasing performance from 1 to 128 processors across a wide range of scene complexities. It is shown that minimal modifications to the algorithm will adapt it for use on shared memory architectures as well.

Bokhari, Shahid H.: *Complete exchange on the iPSC-860.* ICASE Report No. 91-4, January 11, 1991, 32 pages. Submitted to the 1991 International Conference on Parallel Processing.

The implementation of complete exchange on the circuit switched Intel iPSC-860 hypercube is described. This pattern, also known as all-to-all personalized communication, is the densest requirement that can be imposed on a network. On the iPSC-860, care needs to be taken to avoid edge contention, which can have a disastrous impact on communication time. There are basically two classes of algorithms that achieve contention free complete exchange. The first contains the classical standard exchange algorithm that is generally useful for small message sizes. The second includes a number of optimal or near-optimal algorithms that are best for large messages.

Measurements of communication overhead on the iPSC-860 are given and a notation for analyzing communication link usage is developed. It is shown that for the two classes of algorithms, there is substantial variation in performance with synchronization technique and choice of message protocol. Timings of six implementations are given; each of these is useful over a particular range of message size and cube dimension.

Since the complete exchange is a superset of all communication patterns, these timings represent upper bounds on the time required by an arbitrary communication requirement. These results indicate that the programmer needs to evaluate several possibilities before finalizing an implementation—a careful choice can lead to very significant savings in time.

Bokhari, Shahid H.: *Multiphase complete exchange on a circuit switched hypercube.* ICASE Report No. 91-5, January 8, 1991, 24 pages. Submitted to 1991 International Conference on Parallel Processing.

On a distributed memory parallel computer, the complete exchange (all-to-all personalized) communication pattern requires each of n processors to send a different block of data to each of the remaining $n-1$ processors. This pattern is at the heart of many important algorithms, most notably the matrix transpose.

For a circuit switched hypercube of dimension d ($n = 2^d$), two algorithms for achieving complete exchange are known. These are (1) the Standard Exchange approach that employs d transmissions of size 2^{d-1} blocks each and is useful for small block sizes, and (2) the Optimal Circuit Switched algorithm that employs $2^d - 1$ transmissions of 1 block each and is best for large block sizes.

A unified multiphase algorithm is described that includes these two algorithms as special cases. The complete exchange on a hypercube of dimension d and block size m is achieved by carrying out k partial exchanges on subcubes of dimension $d_i, \Sigma_{i=1}^{k} d_i = d$ and effective block size $m_i = m2^{d-d_i}$. When $k = d$ and all $d_i = 1$, this corresponds to algorithm (1) above. For the case of $k = 1$ and $d_1 = d$, this becomes the circuit switched algorithm (2). Changing the subcube dimensions d_i varies the effective block size and permits a compromise between the data permutation and block transmission overhead of (1) and the startup overhead of (2).

For a hypercube of dimension d, the number of possible combinations of subcubes is $p(d)$, the number of partitions of the integer d. This is an exponential but very slowly growing function (e.g. $p(7) = 15, p(10) = 42$) and it is feasible to enumerate over these partitions to discover the best combination for a given message size.

This approach has been analyzed for, and implemented on, the Intel iPSC-860 circuit switched hypercube. Measurements show good agreement with predictions and demonstrate that the multiphase approach can substantially improve performance for block sizes in the 0–160 byte range. This range, which corresponds to 0–40 floating point numbers per processor, is commonly encountered in practical numeric applications. The multiphase technique is applicable to all circuit-switched hypercubes that use the common 'e-cube' routing strategy.

Duck, Peter W., and Mehdi R. Khorrami: *On the effects of viscosity on the stability of a trailing-line vortex.* ICASE Report No. 91-6, January 10, 1991, 32 pages. Submitted to J. Fluid Mechanics.

The linear stability of the Batchelor (1964) vortex is investigated. Particular emphasis is placed on modes found recently in a numerical study by Khorrami (1991). These modes have a number of features very distinct from those found previously for this vortex, including (i) exhibiting small growth rates at large Reynolds numbers and (ii) susceptibility to destabilisation by viscosity. In this paper these modes are described using asymptotic techniques, producing results which compare very favourably with fully numerical results at large Reynolds numbers.

Jordan, Harry F.: *Shared versus distributed memory multiprocessors.* ICASE Report No. 91-7, January 10, 1991, 19 pages. To appear in the Proceedings of European Centre for Medium Range Weather Forecasts workshop on Use of Parallel Processors in Meteorology, Nov. 26-30, 1990.

The question of whether multiprocessors should have shared or distributed memory has attracted a great deal of attention. Some researchers argue strongly for building distributed memory machines, while others argue just as strongly for programming shared memory multiprocessors. A great deal of research is underway on both types of parallel systems. This paper puts special emphasis on systems with a very large number of processsors for computation intensive tasks and considers research and implementation trends. It appears that the two types of system will likely converge to a common form for large scale multiprocessors.

Harten, Ami: *Recent developments in shock-capturing schemes.* ICASE Report No. 91-8, January 22, 1991, 13 pages. To appear in Proc. of the International Congress of Mathematicians 1990, Kyoto, Japan.

In this paper we review the development of the shock-capturing methodology, paying special attention to the increasing nonlinearity in its design and its relation to interpolation. It is well-known that high-order approximations to a discontinuous function generate spurious oscillations near the discontinuity (Gibbs phenomenon). Unlike standard finite-difference methods which use a fixed stencil, modern shock-capturing schemes use an adaptive stencil which is selected according to the local smoothness of the solution. Near discontinuities this technique automatically switches to one-sided approximations, thus avoiding the use of discontinuous data which brings about spurious oscillations.

Speziale, Charles G., and Sutanu Sarkar: *Second-order closure models for supersonic turbulent flows.* ICASE Report No. 91-9, January 23, 1991, 24 pages. AIAA 29th Aerospace Sciences Meeting.

Recent work by the authors and their colleagues on the development of a second-order closure model for high-speed compressible flows is reviewed. This turbulence closure is based on the solution of modeled transport equations for the Favre-averaged Reynolds stress tensor and the solenoidal part of the turbulent dissipation rate. A new model for the compressible dissipation is used along with traditional gradient transport models for the Reynolds heat flux and mass flux terms. Consistent with simple asymptotic analyses, the deviatoric part of the remaining higher-order correlations in the Reynolds stress transport equation are modeled by a variable density extension of the newest incompressible models. The resulting second-order closure model is tested in a variety of compressible turbulent flows which include the decay of isotropic turbulence, homogeneous shear flow, the supersonic mixing layer, and the supersonic flat-plate turbulent boundary layer. Comparisons between the model predictions and the results of physical and numerical experiments are quite encouraging.

Chen, Yen-Ming, Yuh-Roung Ou, and Arne J. Pearlstein: *Development of the wake behind a circular cylinder impulsively started into rotatory and rectilinear motion: Intermediate rotation rates.* ICASE Report No. 91-10, January 24, 1991, 61 pages. Submitted to Journal of Fluid Mechanics.

The temporal development of two-dimensional viscous incompressible flow generated by a circular cylinder started impulsively into steady rotatory and rectilinear motion is studied by integration of a velocity/vorticity formulation of the governing equations, using an explicit finite-difference/pseudo-spectral technique and a new implementation of the Biot-Savart law. Results are presented for a Reynolds number of 200 (based on the cylinder diameter $2a$ and the magnitude U of the rectilinear velocity) for several values of the angular/rectilinear speed ratio $\alpha = \Omega a/U$ (where Ω is the angular speed) up to 3.25. For values of $\alpha \geq 1$, out extension of the computations to larger dimensionless times than those possible in the experimental work of Badr & Dennis (1985) allows for a more complete discussion of the long-term development of the wake. We also discuss several aspects of the kinematics and dynamics of the flow not considered earlier. For higher values of α, our results indicate that for $Re = 200$, vortex shedding does indeed occur for $\alpha = 3.25$ (and possibly for higher values of α also), in contrast to the conclusion of Coutanceau & M'enard (1985). The shedding process is, however, very different from that which gives rise to the usual K'arm'an vortex street for $\alpha = 0$. In particular, consecutive vortices shed by the body can be shed from the same side, and be of the same sense, in contrast to the nonrotating case, in which mirror-image vortices of opposite sense are shed alternately on opposite sides of the body. The implications of the results are discussed in relation to the possibility of suppressing vortex shedding by open- or closed-loop control of the rotation rate.

Mavriplis, D. J., and L. Martinelli: *Multigrid solution of compressible turbulent flow on unstructured meshes using a two-equation model.* ICASE Report No. 91-11, January 31, 1991, 41 pages. Submitted to AIAA Journal.

The steady-state solution of the system of equations consisting of the full Navier-Stokes equations and two turbulence equations has been obtained using a multigrid strategy on unstructured meshes. The flow equations and turbulence equations are solved in a loosley coupled manner. The flow equations are advanced in time using a multi-stage Runge-Kutta time stepping scheme with a stability bound local time-step, while the turbulence equations are advanced in a point-implicit scheme with a time-step which guarantees stability and positivity. Low Reynolds number modifications to the original two-equation model are incorporated in a manner which results in well behaved equations of arbitrarily small wall distances. A variety of aerodynamic flows are solved for, initializing all quantities with uniform freestream values. Rapid and uniform convergence rates for the flow and turbulence equations are observed.

Saltz, Joel, Serge Petiton, and Harry Berryman: *Performance effects of irregular communications patterns on massively parallel multiprocessors.* ICASE Report No. 91-12, January 31, 1991, 22 pages. Journal of Parallel and Distributed Computing.

We conduct a detailed study of the performance effects of irregular communications patterns on the CM-2. We characterize the communications capabilities of the CM-2 under a variety of controlled conditions.

In the process of carrying out our performance evaluation, we develop and make extensive use of a parameterized synthetic mesh. In addition we carry out timings with unstructured meshes generated for aerodynamic codes and a set of sparse matrices with banded patterns of non-zeros. This benchmarking suite stresses the communications capabilities of the CM-2 in a range of different ways. Our benchmark results demonstrate that it is possible to make effective use of much of the massive concurrency available in the communications network.

Wu, Janet, Joel Saltz, Harry Berryman, and Seema Hiranandani: *Distributed memory compiler design for sparse problems.* ICASE Report No. 91-13, January 31, 1991, 40 pages. Submitted to IEEE Trans. Software Engng.

In this paper we describe and demonstrate a compiler and runtime support mechanism. The methods presented here are capable of solving a wide range of sparse and unstructured problems in scientific computing. The compiler takes as input a Fortran 77 program enhanced with specifications for distributing data, and the compiler outputs a message passing program that runs on a distributed memory computer. The runtime support for this compiler is a library of primitives designed to efficiently support irregular patterns of distributed array accesses and irregular distributed array partitions. We present a variety of Intel iPSC/860 performance results obtained through the use of this compiler.

Smith, R.C., K.L. Bowers, and C.R. Vogel: *Numerical recovery of material parameters in Euler-Bernoulli beam models.* ICASE Report No. 91-14, February 5, 1991, 38 pages. Submitted to Journal of Mathematical Systems and Control.

A fully Sinc-Galerkin method for recovering the spatially varying stiffness parameter in fourth-order time-dependent problems with fixed and cantilever boundary conditions is presented. The forward problems are discretized with a sinc basis in both the spatial and temporal domains. This yields an approximate solution which converges exponentially and is valid on the infinite time interval. When the forward methods are applied to parameter recovery problems, the resulting inverse problems are ill-posed. Tikhonov regularization is applied and the resulting minimization problems are solved via a quasi-Newton/trust region algorithm. The L-curve method is used to determine an appropriate value of the regularization parameter. Numerical results which highlight the method are given for problems with both fixed and cantilever boundary conditions.

Smith, R.C., and K.L. Bowers: *A fully Galerkin method for the recovery of stiffness and damping parameters in Euler-Bernoulli beam models.* ICASE Report No. 91-15, February 5, 1991, 22 pages. Submitted to Proc. of the Second Conference on Computation and Control.

A fully Sinc-Galerkin method for recovering the spatially varying stiffness and damping parameters in Euler-Bernoulli beam models is presented. The forward problems are discretized with a sinc basis in both the spatial and temporal domains thus yielding an approximate solution which converges exponentially and is valid on the infinite time interval. Hence the method avoids the time-stepping which is characteristic of many of the forward

schemes which are employed in parameter recovery algorithms. Tikhonov regularization is used to stabilize the resulting inverse problem, and the L-curve method for determining an appropriate value of the regularization parameter is briefly discussed. Numerical examples are given which demonstrate the applicability of the method for both individual and simultaneous recovery of the material parameters.

Thangam, S., R. Abid, and C.G. Speziale: *Application of a new $K-\tau$ model to near wall turbulent flows.* ICASE Report No. 91-16, February 5, 1991, 11 pages. To be submitted to AIAA Journal.

A recently developed $K-\tau$ model for near wall turbulent flows is applied to two severe test cases. The turbulent flows considered include the incompressible flat plate boundary layer with adverse pressure gradients and incompressible flow past a backward facing step. Calculations are performed for this two-equation model using an anisotropic as well as isotropic eddy-viscosity. The model predictions are shown to compare quite favourably with experimental data.

Balachandar, S., and L. Sirovich: *Probability distribution functions in turbulent convection.* ICASE Report No. 91-17, February 11, 1991, 40 pages. Submitted to Physics of Fluids.

Results of an extensive investigation of probability distribution functions (pdfs) for Rayleigh-Bénard convection, in the hard turbulence regime, is presented. It is seen that the pdfs exhibit a high degree of internal universality. In certain cases this universality is established within two Kolmogorov scales of a boundary. A discussion of the factors leading to universality is presented.

Jordan, Harry F.: *Digital optical computers at the optoelectric computing systems center.* ICASE Report No. 91-18, February 11, 1991, 20 pages. Submitted to the International Congress on Optical Science and Engineering, ECO'4, The Hague, The Netherlands, March 11-15, 1991.

The Digital Optical Computing Program within the National Science Foundation Engineering Research Center for Optoelectronic Computing Systems has as its specific goal research on optical computing architectures suitable for use at the highest possible speeds. The program can be targeted toward exploiting the time domain because other programs in the Center are pursuing research on parallel optical systems, exploiting optical interconnection and optical devices and materials. Using a general purpose computing architecture as the focus, we are developing design techniques, tools and architectures for operation at the speed of light limit. Experimental work is being done with the somewhat low speed components currently available but with architectures which will scale up in speed as faster devices developed. The design algorithms and tools developed for a general purpose, stored program computer are being applied to other systems such as optically controlled optical communications networks.

Gropp, William D., and David E. Keyes: *Domain decomposition with local mesh refinement.* ICASE Report No. 91-19, February 22, 1991, 32 pages. Submitted to SIAM Journal of Scientific and Statistical Computation.

We describe a preconditioned Krylov iterative algorithm based on domain decomposition for linear systems arising from implicit finite-difference or finite-element discretizations of partial differential equation problems requiring local mesh refinement. To keep data structures as simple as possible for parallel computing applications, we define the fundamental computational unit in the algorithm as a subregion of the domain spanned by a locally uniform tensor-product grid, called a tile. In the tile-based domain decomposition approach, two levels of discretization are considered at each point of the domain: a global coarse grid defined by tile vertices only, and a local fine grid where the degree of resolution can vary from tile to tile. One global level and one local level provide the flexibility required to adaptively discretize a diverse collection of problems on irregular regions and solve them at convergence rates that deteriorate only logarithmically in the finest mesh parameter, with the coarse tessellation held fixed. A logarithmic departure from optimality seems to be a reasonable compromise for the simplicity of the composite grid data structure and concomitant regular data exchange patterns in a multiprocessor environment. We report some experiments with up to 1024 tiles, comment on the evolution of the algorithm, and contrast it with optimal nonrefining two-level algorithms and optimal refining multilevel algorithms. Computational comparisons with some other popular methods are presented.

Gropp, William D., and David E. Keyes: *Domain decomposition methods in computational fluid dynamics.* ICASE Report No. 91-20, February 22, 1991, 24 pages. Submitted to International Journal of Numerical Methods in Fluids.

The divide-and-conquer paradigm of iterative domain decomposition, or substructuring, has become a practical tool in computational fluid dynamics applications because of its flexibility in accommodating adaptive refinement through locally uniform (or quasi-uniform) grids, its ability to exploit multiple discretizations of the operator equations, and the modular pathway it provides towards parallelism. We illustrate these features on the classic model problem of flow over a backstep using Newton's method as the nonlinear iteration. Multiple discretizations (second-order in the operator and first-order in the preconditioner) and locally uniform mesh refinement pay dividends separately, and they can be combined synergistically. We include sample performance results from an Intel iPSC/860 hypercube implementation.

Tanveer, S.: *Singularities in water waves and Rayleigh-Taylor instability.* ICASE Report No. 91-21, February 15, 1991, 39 pages. Submitted to Proc. Roy. Soc. LONDON A.

This paper is concerned with singularities in inviscid two dimensional finite amplitude water waves and inviscid Rayleigh-Taylor instability. For the deep water gravity waves of permanent form, through a combination of analytical and numerical methods, we present results describing the precise form, number and location of singularities in the unphysical domain as the wave height is increased. We then show how the information on the singularity can be used to calculate water waves numerically in a relatively efficient fashion. We also show that for two dimensional water waves in a finite depth channel, the nearest singularity in the unphysical region has the same form as for deep water waves. However, associated

with such a singularity, there is a series of image singularities at increasing distances from the physical plane with possibly different behavior. Further, for the Rayleigh-Taylor problem of motion of fluid over vacuum, and for the unsteady water wave problem, we derive integro-differential equations valid in the unphysical region and show how these equations can give information on the nature of singularities for arbitrary initial condiuions.

Smyrlis, Yiorgos S., and Demetrious T. Papageorgiou: *Predicting chaos for infinite dimensional dynamical systems: The Kuramoto-Sivashinsky equation, a case study.* ICASE Report No. 91-22, February 19, 1991, 14 pages. Submitted to Proceedings of the National Academy of Sciences, USA.

The results of extensive computations are presented in order to accurately charaterize transitions to chaos for the Kuramoto-Sivashinsky equation. In particular we follow the oscillatory dynamics in a window that supports a complete sequence of period doubling bifurcations preceding chaos. As many as thirteen period doublings are followed and used to compute the Feigenbaum number for the cascade and so enable, for the first time, an accurate numerical evaluation of the theory of universal behavior of nonlinear systems, for an infinite dimensional dynamical system. Further more, the dynamics at the threshold of chaos exhibit a fractal behavior which is demonstrated and used to compute a universal scaling factor that enables the self-similar continuation of the solution into a chaotic regime.

Thangam, S., and C.G. Speziale: *Turbulent separated flow past a backward-facing step: A critical evaluation of two-equation turbulence models.* ICASE Report No. 91-23, February 20, 1991, 27 pages. Submitted to Physics of Fluids A.

The ability of two-equation turbulence models to accurately predict separated flows is analyzed from a combined theoretical and computational standpoint. Turbulent flow past a backward facing step is chosen as a test case in an effort to resolve the variety of conflicting results that have been published during the past decade concerning the performance of two-equation models. It is found that the errors in the reported predictions of the $K - \varepsilon$ model have two major origins: (1) numerical problems arising from inadequate resolution, and (2) inaccurate predictions for normal Reynolds stress differences arising from the use of an isotropic eddy viscosity. Inadequacies in near wall modeling play a substantially smaller role. Detailed calculations are presented which strongly indicate that the standard $K - \varepsilon$ – when modified with an independently calibrated anisotropic eddy viscosity – can yield surprisingly good predictions for the backstep problem.

Jacobs, P.A., and R.J. Stalker: *Mach 4 and Mach 8 axisymmetric nozzles for a shock tunnel.* ICASE Report No. 91-24, February 26, 1991, 26 pages. To be submitted to the Aeronautical Journal.

This study examines the performance of two axisymmetric nozzles which were designed to produce uniform, parallel flow with nominal Mach numbers of 4 and 8. A free-piston-driven shock tube was used to supply the nozzle with high-temperature, high-pressure test gas. The inviscid design procedure treated the nozzle expansion in two stages. Close to

the nozzle throat, the nozzle wall was specified as conical and the gas flow was treated as a quasi-one-dimensional chemically-reacting flow. At the end of the conical expansion, the gas was assumed to be calorically perfect and a contoured wall was designed (using Method-of-Characteristics) to convert the source flow into a uniform and parallel flow at the end of the nozzle. Performance was assessed by measuring Pitot pressures across the exit plane of the nozzles and, over the range of operating conditions examined, the nozzles produced satisfactory test flows. However, there were flow disturbances in the Mach 8 nozzle flow that persisted for significant times after flow initiation.

Mavriplis, Dimitri J.: *Unstructured and adaptive mesh generation for high Reynolds number viscous flows.* ICASE Report No. 91-25, February 27, 1991, 25 pages. Proceedings of the 3rd International Conference on Numerical Grid Generation Conference to be held in Barcelona, SPAIN, June 3-7, 1991.

A method for generating and adaptively refining a highly stretched unstructured mesh, suitable for the computation of high-Reynolds-number viscous flows about arbitrary two-dimensional geometries has been developed. The method is based on the Delaunay triangulation of a predetermined set of points and employs a local mapping in order to achieve the high stretching rates required in the boundary-layer wake regions. The initial mesh-point distribution is determined in a geometry-adaptive manner which clusters points in regions of high curvature and sharp corners. Adaptive mesh refinement is achieved by adding new points in regions of large flow gradients, and locally retriangulating, thus obviating the need for global mesh regeneration. Initial and adapted meshes about complex multi-element airfoil geometries are shown and compressible flow solutions are computed on these meshes.

Cai, Wei, and Chi-Wang Shu: *Uniform high order spectral methods for one and two dimensional Euler equations.* ICASE Report No. 91-26, March 5, 1991, 52 pages. Submitted to Journal of Computational Physics.

In this paper we study uniform high order spectral methods to solve multi-dimensional Euler equations for gas dynamics. Uniform high order spectral approximations with spectral accuracy in smooth regions of solutions are constructed by introducing the idea of the Essentially Non-Oscillatory (ENO) polynomial interpolations into the spectral methods. Based on the new approximations, we propose nonoscillatory spectral methods which possess the properties of both upwinding difference schemes and spectral methods. We present numerical results for the inviscid Burgers' equation, and for one dimensional Euler equations including the interactions between a shock wave and density disturbance, Sod's and Lax's shock tube problems, and the blast wave problem. Finally, we simulate the interaction between a Mach 3 two dimensional shock wave and a rotating vortex.

Banks, H. T., G. Propst, and R. J. Silcox: *A comparison of time domain boundary conditions for acoustic waves in wave guides.* ICASE Report No. 91-27.

We consider several types of boundary conditions in the context of time domain models for acoustic waves. Experiments with different duct terminations (hardwall, free radiation,

foam, wedge) were carried out in a wave duct from which reflection coefficients over a wide frequency range were obtained. These reflection coefficients are used to estimate parameters in the time domain boundary conditions and a comparison of the relative merits of the models in describing the data is presented.

Nicolaides, R.A.: *Analysis and convergence of the MAC Scheme. 1. The linear problem.* ICASE Report No. 91-28, March 11, 1991, 18 pages. Submitted to SIAM Journal of Numerical Analysis.

The MAC discretization of fluid flow is analyzed for the stationary Stokes equations. It is proved that the discrete approximations do in fact converge to the exact solutions of the flow equations. Estimates using mesh dependent norms analogous to the standard $\mathbf{H}^1$ and L^2 norms are given for the velocity and pressure respectively.

Sarkar, S., G. Erlebacher, and M. Y. Hussaini: *Direct simulation of compressible turbulence in a shear flow.* ICASE Report No. 91-29, March 13, 1991, 41 pages. Submitted to Theoretical and Computational Fluid Dynamics.

The purpose of this study is to investigate compressibility effects on the turbulence in homogeneous shear flow. We find that the growth of the turbulent kinetic energy decreases with increasing Mach number - a phenomenon which is similar to the reduction of turbulent velocity intensities observed in experiments on supersonic free shear layers. An examination of the turbulent energy budget shows that both the compressible dissipation and the pressure-dilatation contribute to the decrease in the growth of kinetic energy. The pressure-dilatation is predominantly negative in homogeneous shear flow, in contrast to its predominantly positive behavior in isotropic turbulence. The different signs of the pressure-dilatation are explained by theoretical consideration of the equations for the pressure variance and density variance. We obtained previously the following results for isotropic turbulence; first, the normalized compressible dissipation is of $O(M_t^2)$, and second, there is approximate equipartition between the kinetic and potential energies associated with the fluctuating compressible mode. Both these results have now been substantiated in the case of homogeneous shear. The dilatation field is significantly more skewed and intermittent than the vorticity field. Strong compressions seem to be more likely than strong expansions.

Pruett, C. David, Lian L. Ng, and Gordon Erlebacher: *On the nonlinear stability of a high-speed, axisymmetric boundary layer.* ICASE Report No. 91-30, March 19, 1991, 46 pages. To be submitted to Physics of Fluids.

The stability of a high-speed, axisymmetric boundary layer is investigated using secondary instability theory and direct numerical simulation. Parametric studies based on temporal secondary instability theory indentify subharmonic secondary instability as a likely path to transition on a cylinder at Mach 4.5. The theoretical predictions are validated by direct numerical simulation of temporally-evolving primary and secondary disturbances in an

axisymmetric boundary-layer flow. At small amplitudes of the secondary disturbance, predicted growth rates agree to several significant digits with values obtained from the spectrally-accurate solution of the compressible Navier-Stokes equations. Qualitative agreement persists to large amplitudes of the secondary disturbance. Moderate transverse curvature is shown to significantly affect the growth rate of axisymmetric "second mode" disturbances, the likely candidates of primary instability. The influence of curvature on secondary instability is largely indirect but most probably significant, through modulation of the primary disturbance amplitude. Subharmonic secondary instability is shown to be predominantly inviscid in nature, and to account for spikes in the Reynolds stress components at or near the critical layer.

Cai, Wei, David Gottlieb, and Chi-Wang Shu: *On one-sided filters for spectral Fourier approximations of discontinuous functions.* ICASE Report No. 91-31, March 28, 1991, 19 pages. Submitted to SIAM Journal of Numerical Analysis.

In this paper we prove the existence of one-sided filters, for spectral Fourier approximations of discontinuous functions, which can recover spectral accuracy up to the discontinuity from one side. We also use a least square procedure to construct such a filter and test it on several discontinuous functions numerically.

Cockburn, Bernardo, and Chi-Wang Shu: *The P^1 – RKDG method for two-dimensional Euler equations of gas dynamics.* ICASE Report No. 91-32, March 28, 1991, 12 pages. Submitted to Second International Symposium on High Performance Computing.

We continue our earlier work on a class on nonlinearly stable Runge-Kutta local projection discontinuous Galerkin (RKDG) finite element methods for conservation laws. Two-dimensional Euler equations for gas dynamics are solved using P^1 elements. We discuss the generalization of the local projection, which for scalar nonlinear conservation laws was designed to satisfy a local maximum principle, to systems of conservation laws such as the Euler equations of gas dynamics using local characteristic decompositions. Numerical examples include the standard regular shock reflection problem, the forward facing step problem and the double Mach reflection problem. These preliminary numerical examples are chosen to show the capacity of our approach to obtain nonlinearly stable results comparable with the modern nonoscillatory finite difference methods. Generalizations to P^k elements with $k > 1$ and the use of adaptive triangulations to minimize local errors constitute ongoing research.

Bryan, Kurt: *Numerical recovery of certain discontinuous electrical conductivities.* ICASE Report No. 91-33, March 28, 1991, 28 pages. Submitted to Inverse Problems.

The inverse problem of recovering an electrical conductivity of the form $\gamma(x) = 1 + (k-1)\chi_D$ (χ_D is the characteristic function of D) on a region $\Omega \subset \mathbb{R}^2$ from boundary data is considered, where $D \subset\subset \Omega$ and k is some positive constant. A linearization of the forward problem is formed and used in a least squares output method for approximately solving the inverse problem. Convergence results are proved and some numerical results presented.

ICASE INTERIM REPORTS

Eidson, T. M., and T. A. Zang: *Filtering analysis of a direct numerical simulation of the turbulent Rayleigh-Benard problem.* Interim Report No. 15, December 3, 1990, 49 pages.

A filtering analysis of a turbulent flow has been developed which provides details of the path of the kinetic energy of the flow from its creation via thermal production to its dissipation. A low-pass spatial filter is used to split the velocity and the temperature field into a filtered component (composed mainly of scales larger than a specific size, nominally the filter width) and a fluctuation component (scales smaller than a specific size). Variables derived from these fields can fall into one of the above two ranges or be composed of a mixture of scales dominated by scales near the specific size. The filter is used to split the kinetic energy equation into three equations corresponding to the three scale ranges described above.

The data from a direct simulation of the Rayleigh-Benard problem for conditions where the flow is turbulent is used to calculate the individual terms in the three kinetic energy equations. This is done for a range of filter widths. These results are used to study the spatial location and the scale range of the thermal energy production, the cascading of kinetic energy, the diffustion of kinetic energy and the energy dissipation. These results are used also to evaluate two subgrid models typically used in large-eddy simulations of turbulence. Subgrid models attempt to model the energy below the filter width that is removed by a low-pass filter.

Jacobs, P.A., R.G. Morgan, R.C. Rogers, M. Wendt, C. Brescianini, A. Paull, and G. Kelly: *Preliminary calibration of a generic scramjet combustor.* Interim Report No. 16, March 22, 1991, 31 pages.

The results of a preliminary investigation of the combustion of hydrogen fuel at hypersonic flow conditions are provided. The tests were performed in a generic, constant-area combustor model with test gas supplied by a free-piston-driven reflected-shock tunnel. Static pressure measurements along the combustor wall indicated that burning did occur for combustor inlet conditions of $P_{static} \simeq 19kPa$, $T_{static} \simeq 1080K$ and $U \simeq 3630m/s$ with a fuel equivalence ratio $\phi \simeq 0.9$. These inlet conditions were obtained by operating the tunnel with stagnation enthalpy $H_s \simeq 8.1MJ/kg$, stagnation pressure $P_s \simeq 52MPa$ and a contoured nozzle with a nominal exit Mach number of 5.5.

ICASE COLLOQUIA

October 1, 1990 through March 31, 1991

Name/Affiliation/Title	Date
Dr. Saul Abarbanel, Tel-Aviv University and ICASE "Spurious Frequencies as a Result of Numerical Boundary Treatments"	October 3
Dr. Rahul Simha, The College of William and Mary "Optimization of Resource Control in Commmunication Systems"	October 12
M. Zubair, Old Dominion University "Parallel Partitioning of Sparse Matrices"	October 16
Patrick deBondeli, CR2A, France and Dennis B. Mulcare, LASC-Georgia "Concurrent Embedded System Architecture Design Methods"	October 16
Dr. Eli Reshotko, Case Western Reserve University "Effect of Elevated Free-Stream Turbulence on Turbulent Skin Friction"	October 18
Vidyadhar Y. Mudkavi, California Institute of Technology "Axisymmetric Waves in Vortex Filaments"	October 22
Dr. Richard Barnwell, NASA Langley Research Center "Nonadiabatic and Three-Dimensional Effects in Compressible Turbulent Boundary Layers"	October 23
Cathy Westbury, Queen's University, Ontario, Canada "Turbulent Cooling Flows in Clusters of Galaxies"	October 24
Professor Harry Jordan, University of Colorado "Time-Space Trade Offs in Optical Computing"	November 1
Andy Kopser, Supercomputing Research Center "SPLASH: A Linear Reconfigurable Logic Array"	November 2
Dr. Randolph A. Graves, Supercomputing Systems, Inc. "Distributed Memory Parallel Processing with High-Performance Communications"	November 5

Name/Affiliation/Title	Date
Dr. Sedat Biringen, University of Colorado "Numerical Simulations of Incompressible and Compressible Flow Stability"	November 5
Professor Lotfi Zadeh, University of California, Berkeley "Fuzzy Logic and its Applications"	November 6
Dr. Yuh-Roung Ou, ICASE "Control of a Cylinder Wake by Rotation"	November 6
Dr. Linda Kral, McDonnell Douglas Research Laboratories "Computational Studies in Transition and Turbulence"	November 7
Dr. Hassan Aref, University of California at San Diego "Lagrangian CFD"	November 9
Steven Ashby, Lawrence Livermore National Laboratory "A Matrix Analysis of Conjugate Gradient Algorithms"	November 13
Dr. G. Comte-Bellot, Ecole Centrale de Lyon, France "Propagation of Acoustic Waves Through Turbulence"	November 14
Professor A. M. Yaglom, Institute of Atmospheric Physics, USSR Academy of Sciences "Spectra and Correlation Functions of Turbulence in any Unstably Stratified Atmospheric Surface Layer"	November 14
Professor H. Peerhossaini, University of Nantes - France "Boundary Layer Flow on the Turbine Blade Pressure Side (Gortler Vortex Flow)"	November 15
Dr. Yiorgos Smyrlis, University of California, Los Angeles "The Route to Chaos for the Kuramoto-Sivaskinsky Equation"	November 21
Dr. Craig Douglas, Yale University "A Greatly Simplified Theory for Multigrid Methods"	November 30
Dr. Alvin Bayliss, Northwestern University "Nonlinear Dynamics in Combustion"	December 4
Donald Delisi, Northwest Research Associated, Inc. "New Laboratory Measurements to the Evolution of a Vortex Pair: Is CFD up to the Challenge?"	December 5

Name/Affiliation/Title	Date
Professor Ralph Metcalfe, University of Houston "Large Scale Structures in Reacting Mixing Layers"	December 6
Dr. David Kopriva, The Florida State University "Spectral Solution of Supersonic Flows over Cones and Wedges"	December 10
Dr. Phillip Hall, University of Manchester, England "Vortex Instabilities in Hypersonic Flows: Sutherland Law Fluids and Real Gas Effects"	December 12
Professor Z.U.A. Warsi, Mississippi State University "Numerical Mapping of Arbitrary Domains Using Spectral Methods"	January 4
Professor Anthony P. Reeves, Cornell University "Programming Highly Parallel Multicomputers: The Paragon Approach"	January 9
Xinming A. Lin, University of California, Los Angeles "An Object-Oriented Particle Simulation Approach"	January 11
Dr. Siva M. Mangalam, Analytical Services & Materials, Inc. "Some Advances in Spatial and Temporal Flow Diagnostics Techniques for Flight, Wind Tunnel, and CFC Research"	January 16
Jurgen Schoene, German Aerospace Research Establishment "Design of Supersonic Wings Using an Optimization Strategy Coupled with a Solution Scheme for the Euler Equations"	January 18
Dr. N. Knoll, German Aerospace Research Establishment "A Quadrilateral Based Second-Order TVD Method for Unstructured Adaptive Meshes"	January 18
Dr. Reda R. Mankbadi, NASA Lewis Research Center "Boundary-Layer Transition: Developing a Critical-Layer Theory"	January 23
Dr. Ugo Piomelli, University of Maryland, College Park "A Dynamic Subgrid Scale Stress Model for Large-Eddy Simulations"	February 15
Roldan Pozo, University of Colorado at Boulder "Performance Analysis of Parallel Architectures for Scientific Computing"	February 20
John Van Rosendale, ICASE "An Optimal Parallel Time Multigrid Algorithm"	February 22

Name/Affiliation/Title	Date
Ammar Degani, Lehigh University "The Asymptotic Structure of a Three-Dimensional Turbulent Boundary Layer – Theory and Application"	February 28
Professor Vladimar Rokhlin, Yale University "Fast Evaluation of Functions of Dense Matrices"	March 1
Rupak Biswas, Renssalaer Polytechnic Institute "Parallel Adaptive Methods for Hyperbolic Partial Differential Equations"	March 7
Phil Keenan, University of Chicago "Thermal Simulation of Pipeline Flow"	March 8
James Quirk, Cranfield Institute of Technology "An Adaptive Grid Algorithm for Computational Shock Hydrodynamics"	March 11
Dinshaw Balsara, The Johns Hopkins University "Jet Disruption Using High-Resolution Godunov Schemes"	March 12
Professor Alok N. Choudhury, Syracuse University "FORTRAN77D and FORTRAN90D: Scalable and Portable Software for SIMD and MIMD Distributed Memory Parallel Computers"	March 14
David Kotz, Duke University "Prefetching and Caching Techniques in File Systems for MIMD Multiprocessors"	March 18
Professor David G. Crighton, University of Cambridge, England "The Noise of a Modern Many-Bladed Propeller–Predictions Based on Asymptotic Theory"	March 20
Paul Durbin, Stanford/Ames Center for Turbulence Research "Turbulence Modeling Near Solid Boundaries"	March 28

OTHER ACTIVITIES

A workshop on "Unstructured Scientific Computation on Scalable Multiprocessors" sponsored by ICASE was held at the Ramada Inn, Kill Devil Hills, NC on October 29-31, 1990. Sixty-five people attended. The objective of this workshop was to discuss mathematical and computer science issues related to unstructured scientific computation on multiprocessor systems. A proceedings will be published by the M.I.T. Press.

On December 17-19 ICASE hosted a workshop to identify research opportunities in software of importance to NASA's initiative under the Federal High Performance Computing and Communications (HPCC) program. Approximately 40 people participated representing the NASA centers involved in HPCC and several universities. As a result of the workshop a matrix was created that linked important areas of research in software with organizations that were prepared to pursue the research.

On November 12-13, 1990 a symposium on "Recent Development in Turbulence" was sponsored by ICASE and NASA Langley Research Center was held at the Omni Hotel, Newport News, VA. Forty-eight people attended this symposium. The objectives were to review the latest thrusts in turbulence research, including experimental and theoretical research. Recent work in turbulence modeling, as well as current work on the development of the Proper Orthogonal Decomposition method, was also discussed. Papers from this symposium will be published by Springer-Verlag in a volume entitled *Studies in Turbulence.*

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